INTERNATIONAL ENERGY AGENCY

HYDROGEN & FUEL CELLS

Review of National R&D Programs

OECD

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The International Energy Agency (IEA) is an autonomous body which was established in November 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme.

It carries out a comprehensive programme of energy co-operation among twenty-six* of the OECD's thirty Member countries. The basic aims of the IEA are:

- to maintain and improve systems for coping with oil supply disruptions;
- to promote rational energy policies in a global context through co-operative relations with non-member countries, industry and international organisations;
- to operate a permanent information system on the international oil market;
- to improve the world's energy supply and demand structure by developing alternative energy sources and increasing the efficiency of energy use;
- to assist in the integration of environmental and energy policies.

* *IEA Member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, the Republic of Korea, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, the United States. The European Commission also takes part in the work of the IEA.*

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996), the Republic of Korea (12th December 1996) and Slovakia (28th September 2000). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

FOREWORD

With the oil and gas supply security and climate change emerging as high concerns, the need for new technologies to alleviate dependence on hydrocarbons and reduce carbon dioxide (CO_2) emissions is becoming increasingly urgent. In the mid to long term, this will require significant changes in the way the global energy system is managed and the adoption of an array of new technologies which produce and use energy more efficiently and more cleanly than in the past.

IEA countries have been improving the overall efficiency of their energy systems and developing renewable energy sources for many years. More recently, they have also invested considerable effort in making commercially available technologies to separate and store carbon dioxide from fossil fuels, produce hydrogen from fossil, nuclear and renewable energy sources, and develop fuel cells for clean and efficient use of hydrogen. In addition to reducing emissions in power generation, CO_2 capture and storage would enable hydrogen to be produced from natural gas and coal without incurring significant emissions to the atmosphere. Increasing use of the world's abundant coal reserves to produce CO_2-free electricity and hydrogen would both diversify energy supply and mitigate environmental concerns. Clean, CO_2-free hydrogen produced from fossil fuels and – in the longer term – from nuclear and renewable sources could potentially replace oil and reduce emissions in transport. In turn, fuel cells hold the promise to significantly increase the efficiency of the energy system in both stationary and transport applications with reduced or nearly zero emissions.

The development of cost-effective hydrogen and fuel cells technologies and infrastructure requires time, public and private sector investment, and technology breakthroughs to achieve commercial maturity and market penetration. Many IEA Member countries have already embarked on this effort in close co-operation with industry. Many others are in the process of revising and reinforcing their research and development strategies.

This book is a timely attempt to map the many and various governmental research activities and policies for hydrogen and fuel cells. It provides policymakers and managers with the information needed to exploit synergies and maximise the benefits of international co-operative efforts. The book draws primarily on information contributed by IEA governments through the IEA Hydrogen Co-ordination Group. Such cooperation together with concerted government strategies, long-term commitment and public research activities are indispensable for catalysing larger private R&D investment, for building public awareness and for facilitating the penetration of hydrogen and fuel cells technologies in the competitive marketplace.

Claude Mandil
Executive Director

ACKNOWLEDGEMENTS

The publication of this book was made possible thanks to the contributions of numerous experts. Most of the Members of the IEA Hydrogen Co-ordination Group (HCG) actively contributed providing basic information through questionnaires and short reports, as well as feedback and additions in the course of the work through several review and editing rounds.

Marianne Haug, Director of the IEA Technology Office, provided encouragement and leadership. Carmen Difiglio, Head of the IEA Energy Technology Policy Division, contributed to organise the activities. Giorgio Simbolotti, IEA Energy Technology Collaboration Division, co-ordinated the activities and reviewed the final draft. Jeff Hardy patiently drafted the manuscript and made it a smoothly readable text. Corinne Hayworth, IEA Public Information Office, designed the graphics of the cover page. The work benefited from the financial contribution of the US Department of Energy to support the activities of the Hydrogen Co-ordination Group.

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EXECUTIVE SUMMARY

Technology development and international co-operation are part of the solution to address the energy security and environmental concerns that affect our current energy system. Along with other energy technologies, hydrogen as an energy carrier and fuel cells as a conversion technology are emerging as high-potential options to ensure a CO_2-free, secure energy future. The expectation is that in some decades from now fuel cells and CO_2-free hydrogen produced from fossil, renewable and nuclear energy sources, will be entering the power generation market as well as the transport, industrial and residential sectors, thus playing a significant role in reducing emissions and enhancing global energy security.

This development requires extensive public and private R&D efforts to achieve technology breakthroughs and bring these technologies to commercial maturity. Hydrogen is a well-known industrial gas, used in a number of applications such as refinery, chemical industry, metal manufacturing. As an energy carrier it is flexible and potentially clean. However, its production and use still require energy-consuming and costly processes, and the need for new infrastructure. Similarly, fuel cell performance and cost are far from the economic competitiveness, and their use is currently confined to niche market applications.

Driven by recent technical advances and the increasing needs for diversified and sustainable technologies, in particular in the oil-consuming transport sector, the OECD governments have recently intensified their R&D efforts on hydrogen and fuel cells. A number of new initiatives have significantly increased the global governmental R&D investment to some US$ 1 billion a year. They are equally distributed in the three OECD areas, Asia-Pacific, Europe and North America. Fuel cells absorb more than half this global effort. The rest is invested in technologies to produce, store, transport, and use hydrogen including non-fuel-cell technologies such as hydrogen-fuelled internal combustion engines and gas turbines.

The global spending on hydrogen and fuel cells does not fully emerge in the current statistics for public sector R&D investment in energy technologies. The R&D efforts to produce hydrogen from fossil, nuclear and renewable energy sources are accounted for as spending on advanced fossil, nuclear and renewable technology, respectively, and fuel cell R&D is included in the efforts to improve the efficiency of the end-use technologies and the overall energy system.

Although governmental research is indispensable for catalysing the development process, it is not the dominant part of the current, global R&D effort on hydrogen and fuel cells. Considerably larger – and hardly assessable – is the total R&D investment of the private sector, including major oil & gas companies, vehicle producers, electrical utilities, power plant constructors, and a number of major and small players in the current hydrogen and fuel cell market.

This global effort is expected to continue over the next years as major countries have planned multi-annual investment. This includes: $ 1.7 billion over 5 years in the United States; up to € 2 billion, including renewable energy, in the 6th Framework Program of the European Union; more than ¥ 30 billion a year in Japan; and multi-annual programs in place in other countries such as Canada, Germany, Italy.

Governmental R&D efforts and long-term commitments are complemented by three major international co-operation initiatives.

- In April 2003, twenty-four Member countries of the International Energy Agency accepted the IEA Executive Director's invitation to establish the IEA Hydrogen Co-ordination Group (HCG) to enhance co-ordination among national R&D programs and policy strategies. Under the guidance of the IEA Committee for Energy Research and Technology (CERT), the HCG builds on the IEA international co-operation framework for energy technologies. This includes relevant R&D co-operation projects, such as the IEA Implementing Agreements on Hydrogen, Advanced Fuel Cells, the Greenhouse Gas R&D Program, and other Agreements with interest in specific hydrogen and fuel cell topics (Clean Coal Centre, Bio-Energy, Advanced Motor Fuels, Hybrid Vehicles, Energy Technology System Analysis Project).
- In November 2003, sixteen countries including non-OECD countries such as Brazil, China, India and Russia, joined the International Partnership for Hydrogen Economy (IPHE), a global, high-level political interface proposed by the United Stated to foster public and private co-operation on hydrogen and fuel cells.
- In January 2004, the European Commission established the European Technology Platform for Hydrogen and Fuel Cells, a cluster of public/private R&D initiatives within the Commission's Framework Programs.

The Figure 1 shows a schematic of the global hydrogen and fuel cell R&D effort, and ongoing international co-operation initiatives.

This review of the R&D programs and policy strategies in Member countries maps the national, governmental efforts to research, develop and deploy the interlocking elements that constitute a hydrogen-based energy system, including CO_2 capture and storage when hydrogen is produced using fossil fuels. It is a first-of-kind attempt at providing an overview of what is being done, by whom and in which country, for each R&D and policy topic. The information contained in the report can be collectively considered up-to-date as of August 2004. Given the complexity of the matter and the quickly evolving context – many countries are currently revising their R&D strategies and activities, and a number of new projects are underway – the publication is non-exhaustive. It reflects primarily governmental R&D efforts. Private sector activities are only reflected to the extent that they are conducted in partnership with public organisations. Nevertheless, the *Review* highlights potential international co-operation and is intended to support the work of policy makers and R&D experts in the public and private sectors.

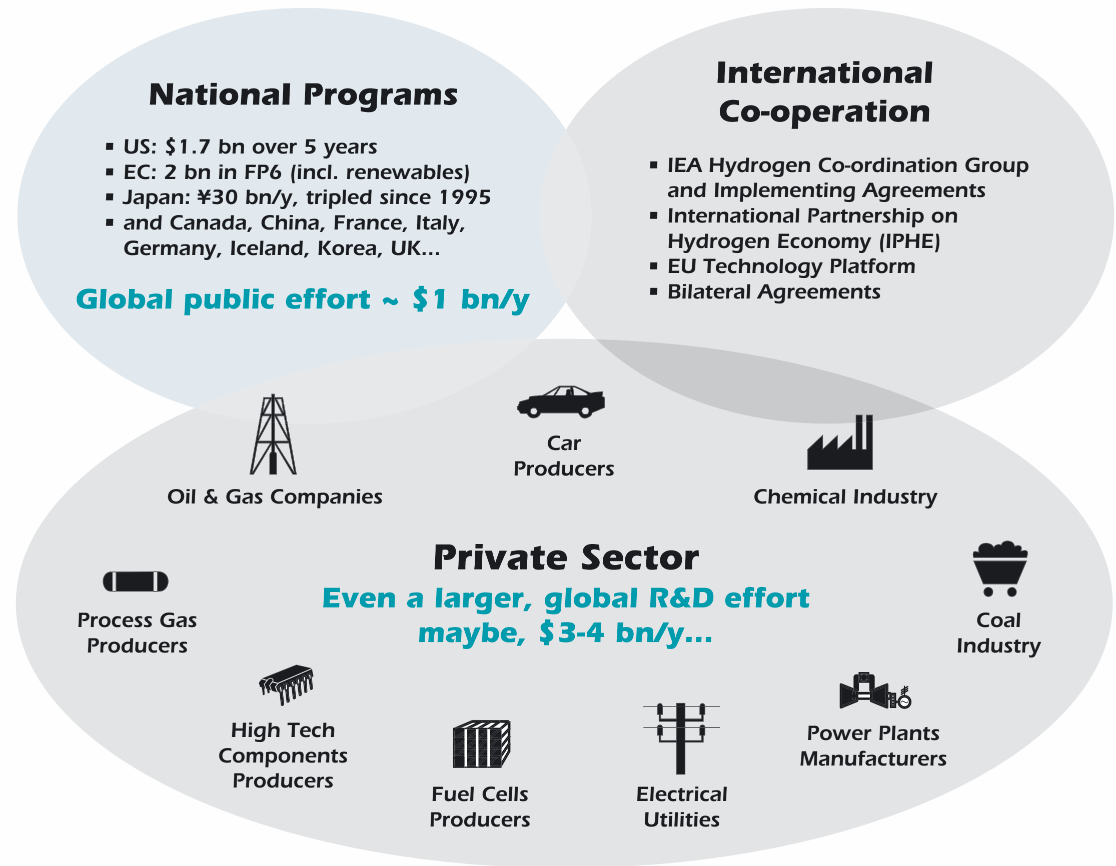
The *Review* comprises two parts. In the first, the huge number of ongoing, national activities and projects are presented in a thematic, cross-country overview reflecting the vast array of technologies, logistics and policy issues required to build a hydrogen-based energy system. Individual country profiles are given in the second section for twenty-three IEA countries.

In the thematic overview the information is organised into six sections. In each section, a brief introduction is provided for each technology, its state of development and important research objectives. Fuel Cells are taken up in Section 1 which includes a review of government work as it relates to each fuel cell type, basic R&D programmes, and fuel cell demonstration projects for both stationary and automotive applications. Hydrogen production is the focus of Section 2, beginning with efforts by type of production method, e.g., production from fossil fuels, renewable and nuclear energy. Since CO_2 capture and storage is considered to be an essential aspect of hydrogen production from fossil fuels, information relating to these R&D programs is also included in this section. Hydrogen

storage, transportation and distribution are covered in Section 3, focusing on activities being undertaken for each of the main storage and transportation technologies. Section 4 provides a synthesis of the activities reported in the areas of hydrogen safety, codes and standards. Section 5 reviews policy studies and delineates policy targets. Section 6 offers some elements of the ongoing efforts to build public awareness and education on hydrogen and fuel cells.

Figure 1

Hydrogen and Fuel Cells – National R&D Efforts and International Co-operation



Taken as a whole, the *Review* draws heavily and primarily upon information contributed by the IEA governments participating in the HCG, submitting responses to a survey questionnaire, and providing feedback through the several review and editing rounds. In the course of the work, HCG representatives were also encouraged to provide additions as appropriate to reflect new developments in their country.

Substantial amounts of information were drawn from presentations and papers provided by governments at various HCG meetings and international conferences over the last year. In many cases, these primary sources of information have been complemented by national reports and official governmental web sites. To the extent that the IEA has produced this report from the large pool of information provided primarily by HCG delegates, it relies on delegates for the accuracy and currency of the findings.

In virtually all the IEA countries, R&D and policy efforts on hydrogen and fuel cells are expanding, ranging from fully integrated, government-funded programs to strategies spread in multiple public and private initiatives. Virtually all of the IEA countries indicate that research into hydrogen and fuel cells is an important element of their programs to develop and deploy advanced, clean energy technologies

Japan and the United States provide examples of fully-integrated, highly-funded programs. In Japan, the New Hydrogen Project (NHP) extends the work initiated during the seminal, 10-year, WE-NET program, which initially focused R&D on technologies necessary for establishing a hydrogen infrastructure (e.g., electrolysis, liquefaction, storage) and later on the utilisation of hydrogen and construction of fuelling stations. Japan not only develops hydrogen technologies, but it also is a leading country in fuel cell development with a strong involvement of the private sector. Under the guidance of the Ministry for Economy, Trade and Industry (METI), the NHP integrates fuel cell development, hydrogen production, transportation and storage technologies concurrently with the implementation of demonstration programs, vehicle sales, construction of refuelling infrastructure, establishment of codes and standards, and a general push to enlarge the consumer market for both stationary and automotive fuel cells.

The U.S. conducts the vast majority of its R&D on hydrogen and fuel cells under the "Hydrogen, Fuel Cells and Infrastructure Technologies Program," which funds research, development, and validation activities linked to public-private partnerships. The program is led by the US Department of Energy (DOE) and integrates the activities of a number of US government agencies, including the Department of Defence, the Department of Transportation and the Environmental Protection Agency.

The government's current role is to focus funding on high-risk, applied research in the early phases of development to the point where the private sector can make informed decisions on whether or not, and how best to commercialise these technologies. With two pillar-initiatives such as the *Hydrogen Fuel Initiative* (US$ 1.2 billion over 5 years) and the *FreedomCar* initiative, the US program seeks to implement the recommendations in the President's National Energy Policy, the DOE Strategic Plan, the National Hydrogen Energy Vision and Roadmap, and the Hydrogen Posture Plan.

Australia's 2003 national hydrogen study recognised the long term potential of hydrogen and fuel cells in relation to transport, portable appliances and distributed generation in remote areas, and the need for Australia to be involved in the development of appropriate international codes and standards for hydrogen and fuel cell use. At national level, Australia's principal public research institution – the Commonwealth Scientific and Industrial Research Organisation, CSIRO – and a number of universities are active in hydrogen R&D. A review of national relevant projects is currently being compiled by CSIRO. Hydrogen research is also an element of the COAL21 program, which includes hydrogen production from coal with carbon sequestration.

Canada's R&D program has been managed by Natural Resources Canada since 1985 and is largely based on a public-private partnership to develop fuel cells and hydrogen technologies with short-to-medium term commercial potential. Proton Exchange Membrane fuel cells developed by Canada are currently fuelling a number of demonstration buses in European and North America cities, testimony to the success of the Canadian program. An important element is also the development of codes and standards for safe use and commercialisation of hydrogen and fuel cells. The Canadian effort has recently been strengthened by the "Climate Change Plan for Canada," which allocates C$130 million to developing a hydrogen economy in Canada, and further C$85 million allocated within the Industry Portfolio to support hydrogen/fuel cell RD&D.

In Germany, the Federal Ministry of Economy and Labour (BMWA) supports research and demonstration of fuel cells and hydrogen within the "Federal Programme for Energy Research and Technologies." Intensive RD&D on hydrogen technologies started in Germany in 1988 and focused on electrolysis, hydrogen storage and larger projects to demonstrate the complete chain of solar hydrogen energy production (HYSOLAR and the Solar-Hydrogen-Bavaria Project BAYSOLAR). This work ended in 1995/1999 with the conclusion that main components were developed and functioning but commercial viability was not proved. As a consequence, since 1995 RD&D efforts were concentrated on fuel cells projects focused on new materials, improved components, and system integration. The "Program on Investment into the Future" (ZIP) includes some 40 projects related to hydrogen technology and demonstration of infrastructure for fuel cell buses. Significant programs are also being conducted at regional levels in Bavaria, Baden-Wurttemberg and North-Rhine Westphalia.

Most of the other R&D programs elsewhere in the OECD are not as integrated as those mentioned above. For example, some 40 Austrian organisations are involved in 50 ongoing hydrogen and/or fuel cell projects. Denmark's strategy during the period 1998-2002 focused on small fuel cells for stationary power as a part of some 34 different projects. Greece is conducting a number of activities in the context of national or EC co-funded projects focusing on islands as an early entry for renewable-based hydrogen technologies. The Netherlands have no hydrogen program but all aspects of hydrogen technology are being investigated, and in 2003 the "Sustainable Hydrogen" project has been launched to stimulate hydrogen related research.

In conclusion, while the book provides a realistic picture of the range of R&D initiatives and projects to develop hydrogen and fuel cells, the high number of technology options under consideration points out that such an effort is only the beginning of a several-decades journey toward a radically changed, sustainable energy system.

INTRODUCTION

Prospects for commercial applications of fuel cells are slowly gaining momentum, largely driven by significant technological advances and expectations. This enables governments to consider turning to hydrogen and fuel cells as a practical foundation for implementing public policies responding to growing environmental concerns and uncertainties about the security and long-term price of oil. With the expectation that fuel cells and hydrogen can play a significant role in the global energy economy, governments are increasing funds for research, development and demonstration of hydrogen and fuel cells and to create programs and enabling conditions to support their use.

The challenge is that most of the required new hydrogen and fuel cell technologies are still in their infancy – compared with the existing conventional energy infrastructure – and major investments, both public and private, will be needed to commercialise the production of hydrogen for energy use.

IEA member governments, as well as non-member governments, recognise that this long-term RD&D effort is required to realise the significant technological potential of hydrogen and fuel cells; and that cooperative efforts among nations can help speed effective progress towards these goals. Auspiciously, the pre-commercial stage of much hydrogen production and fuel cell technology RD&D makes it well suited to collaboration although proprietary issues are associated with pre-commercial technologies.

The objective of this *Review of National R&D Programs* is to assess the current state of play and forward plans by IEA member governments to research, develop and deploy the interlocking pieces of what could become the *hydrogen economy*. The objective is to identify which efforts have been undertaken and where work is currently being done. By beginning to tie together the pieces of the complicated and sprawling hydrogen economy, the IEA aims to exploit the benefits of collaboration among member and non-member governments in the development and commercialisation of hydrogen and fuel cell technologies.

Methodology

This Review of National R&D Programs on hydrogen and fuel cells (HFC) reflects the governmental R&D activities carried out in the IEA countries which are members of the IEA Hydrogen Co-ordination Group (HCG). It is comprised of two parts: (1) a thematic review of hydrogen and fuel cell technologies and related research, development and demonstration projects across the IEA region; and (2) a country-by-country summary of hydrogen and fuel cell R&D efforts in the HCG Member countries.

The basic information for this report was collected using a questionnaire which was completed by the country representatives in the IEA HCG. The results from the questionnaire were used to first produce a country-by-country summary of national hydrogen and fuel cell programmes. Country profiles were reviewed and updated by the HCG delegates. A thematic overview of HFC developments across countries was then prepared to provide readers with an overview of what is going on in any particular area of research, development, demonstration or policy. We have tried to make this thematic summary readable and interesting while still providing a complete picture.

Taken as a whole, the *Review* draws heavily and primarily upon information contributed by the IEA governments participating in the HCG, submitting responses to the survey questionnaire, and providing feedback through the several review and editing rounds. In the course of the work, experts from the HCG were also encouraged to provide additions as necessary to reflect new developments in their country. Substantial amounts of information were also drawn from presentations, speeches and papers provided by governments at various HCG meetings and international conferences over the last year. In many cases, these primary sources of information have been augmented with documentation publicly available from national governments and various program websites.

Although non exhaustive – many IEA countries are currently revising their R&D strategies and programs, and a number of new projects are underway – the information contained in the following pages can be collectively considered as up-to-date as August 2004, and to the extent that the IEA Secretariat has produced this draft from the large pool of information provided primarily by HCG delegates, it relies on delegates to confirm the accuracy and currency of the findings. The report reflects only governmental R&D efforts. Private sector activities are only reflected to the extent that they are conducted in partnership with public organisations.

Information is organized into 6 sections, derived from the primary questions put forth in the questionnaire. Each section features a *chapeau* which provides an introduction to the technology and an overview of its state of development and important research objectives.

Fuel Cells are taken up in Section 1, which begins with a brief overview of fuel cell fundamentals and a synopsis of each of the major fuel cell types. It then provides a review of IEA government work as it relates to each fuel cell type, including R&D efforts directed as specific fuel cell types; a review of programs undertaking basic fuel cell R&D; and, the section concludes with a review of fuel cell demonstrations for transportation and stationary applications.

Hydrogen production is the primary focus of Section 2, starting with a brief overview of hydrogen production techniques and issues. It then delineates IEA government effort by type of production method, e.g., production from fossil fuels. Since CO_2 sequestration is considered to be an essential aspect of hydrogen production techniques which generate CO_2 emissions, information reported by IEA governments is also included in this section.

Hydrogen storage, transportation and distribution are covered in Section 3, focussing on a review of activities being undertaken for each of the main storage technologies. The section also includes a discussion and synthesis of IEA government activities in the area of hydrogen transportation and storage.

Section 4 provides a synthesis of IEA government activities reported in the areas of hydrogen safety and codes and standards. Section 5 reviews policy studies and delineates policy targets for future work. Section 6 offers a brief synthesis of the ongoing efforts to build public awareness and education.

Overview

Virtually all of the IEA countries indicate that research into hydrogen and fuel cells is an important – and in most cases an increasingly important – element of their overall public policy and program planning activities, either as a purposely designed and funded hydrogen and fuel program (HFC),

or an element of an overall energy and environment strategy, or as a specific budget line item found in one or more programs and agencies.

Japan and the United States provide exceptional examples of fully-integrated, highly-funded HFC programs. In Japan, the New Hydrogen Project (NHP) extends the work initiated during the seminal, 10-year, ¥18 billion WE-NET program, which initially focused R&D on core technologies necessary for establishing a hydrogen infrastructure (e.g., electrolysis, liquefaction, storage) and then later on the utilisation of hydrogen and construction of fuelling stations. The NHP, not only ties together a number of METI's ongoing and new programs, but it integrates the development of fuel cell, hydrogen production, and hydrogen transportation and storage technologies concurrently with the implementation of demonstration programs, vehicle sales, construction of refuelling infrastructure, establishment of codes and standards, and a general push to enlarge the consumer market for fuel cells and fuel cell vehicles.

The U.S. conducts the vast majority of its R&D on hydrogen and fuel cells under the "Hydrogen, Fuel Cells and Infrastructure Technologies Program," which funds research, development and validation activities linked to public-private partnerships. The program is led by the US Department of Energy (DOE) and integrates the activities of a number of US government agencies, including the Department of Defence, the Department of Transportation and the Environmental Protection Agency. The government's current role is to concentrate funding on high-risk, applied research in the early phases of development to the point where the private sector can make informed decisions on whether or not, and how best to commercialize these technologies. The program seeks to implement recommendations in the President's National Energy Policy, the DOE Strategic Plan, the National Hydrogen Energy Vision and Roadmap, and the Hydrogen Posture Plan.

Australia is an example where HFC R&D is consistent with the government's objective of reducing the greenhouse gas intensity of energy supply and use. HFC work is also an element of Australia's COAL21 program which includes research into hydrogen production by coal gasification (and employing carbon sequestration) as part of the national clean coal strategy. Australia's national hydrogen study, undertaken in 2003, investigated the longer term potential of hydrogen fuel cells in relation to transport, portable appliances and distributed generation, particularly in remote areas, leading to an energy *White Paper* which acknowledged the long-term importance of hydrogen and the need for Australia to be involved in the development and adoption of appropriate international codes and standards. At the national level, research and development into hydrogen is occurring in a number of universities as well as through *Energy Transformed*, a significant, wide-ranging and long-term initiative of the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia's principal public sector research institution. Through CSIRO, a comprehensive review of Australian hydrogen and fuel cell technology projects is being compiled, and this is expected to be completed before the end of 2004.

Similarly, Canada's HFC R&D work contains various program elements focusing on the development of clean, efficient technologies for the production of hydrogen using renewable or sustainable energy sources. The hydrogen R&D program has been managed by Natural Resources Canada since 1985, and is largely based on cost-shared R&D partnerships with the private sector – focusing primarily on automotive fuel cell technologies, stationary power applications concentrating on Solid Oxide Fuel Cells (SOFC) and portable power using direct methanol fuel cells. Overall, the C$20 million program is oriented toward the development of technologies with short-to-medium term commercial potential. The R&D program focuses on hydrogen production and storage; fuel cell commercialization; and the development of coordinated hydrogen and fuel cell standards that will be required for hydrogen to be a safe and cost-effective energy carrier. Two of Canada's most successful technology

developments have been the Ballard Proton Exchange Membrane fuel cell and the Stuart Energy alkaline water electrolyser. Overall, HFC efforts have recently been strengthened by Canada's C$1 billion "Climate Change Plan for Canada," which allocates C$130 million to developing a hydrogen economy in Canada. A further C$85 million has been re-allocated to support hydrogen/fuel cell RD&D activities.

In Germany, within the Federal Programme for *Energy Research and Energy Technologies* the Federal Ministry of Economics and Labour (BMWA) supports RD&D of fuel cells and hydrogen technologies. Intensive RD&D on hydrogen technologies started in Germany in 1988 and was concentrated on the development of specific technologies like hydrogen production using electrolysis, hydrogen storage and on larger projects to demonstrate the complete supply chain of a solar hydrogen energy economy (HYSOLAR and the Solar-Hydrogen-Bavaria Project BAYSOLAR). This work was concluded in 1995-1999 with the result that in principle the main components of a hydrogen energy system were developed and functioning, however, that commercial viability of a solar hydrogen economy could only be reached in the far future. As a consequence, RD&D was concentrated on fuel cells since 1995 with an annual BMWA budget of €8-10 M per year. Ambitious projects concentrating on new materials, improved components and system integration have been supported. Notably, the *Program on Investment into the Future* (abbreviated "ZIP") includes some 40 projects related to hydrogen technology, such as demonstration of infrastructure for fuel cell buses.

Most of the other HFC programs are not as integrated. For example, despite having no overarching HFC program, some 40 Austrian organizations are involved in 50 ongoing hydrogen and/or fuel cell projects. The Danish fuel cell strategy is oriented towards smaller SOFC and PEMFC stationary power through 34 projects during the period 1998-2002. Greece also does not have a HFC specific program, but conducts a plethora of R&D activities, undertaken by Greek research institutions in the context of national or EC co-funded projects. Islands with isolated electricity grids, for example, have been identified as a case of particular interest for the early entry of renewable-based hydrogen technologies. The French *Reseau Paco* provides and example of a national network developed to promote cooperation between R&D institutes and companies, with the major themes focussed primarily on PEM, SOFC, hydrogen storage and on-board reforming. Additionally, France features innovative research on the development of high-temperature processes for hydrogen production, coupled with future nuclear energy. The Netherlands, like a number of other smaller countries, reports generally that "all aspects of HFC technology are being investigated." As an example of specific, forward-looking projects aimed at bridging renewables to the hydrogen economy, Sweden reports long-term basic research into artificial photosynthesis project using the sunlight directly to produce hydrogen from water.

Regardless of the approach taken on HFC research and development, a vast amount of information was reported in response to the IEA's HCG survey questionnaire. The following pages provide a categorical review of the findings reported to date.

PART 1

THEMATIC OVERVIEW

Chapter 1.
FUEL CELLS

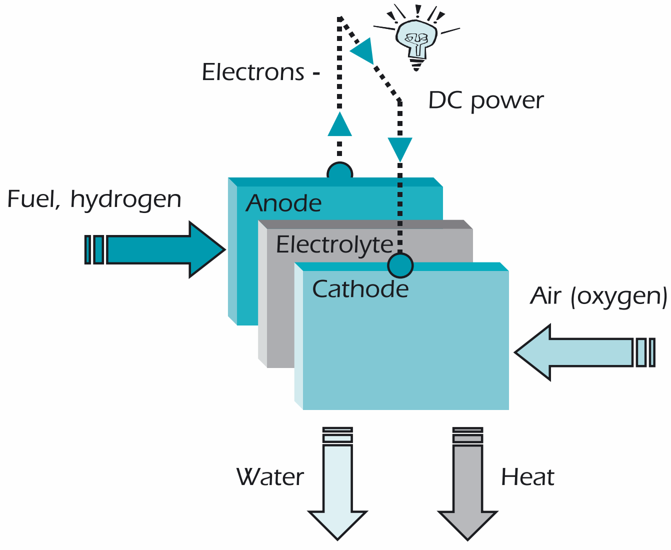
This section delineates the work reported on fuel cells. It starts with a descriptive overview of fuel cell technologies, including a synopsis of each of the major fuel cell types. It then provides a review of IEA government work as it relates to each fuel cell type. The section also includes a summary of general work conducted on basic fuel cell R&D and a review of fuel cell demonstrations for both transportation and stationary applications.

Overview of fuel cells

A fuel cell is a device that uses hydrogen (or hydrogen-rich fuel) and oxygen to create electricity by an electrochemical process. A fuel cell consists of two electrodes – a negative electrode (or anode) and a positive electrode (or cathode) – sandwiched around an electrolyte. Hydrogen is fed to the anode, and oxygen is fed to the cathode. Activated by a catalyst, hydrogen atoms separate into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they reunite with oxygen and the electrons to produce water and heat. For polymer electrolyte membrane and phosphoric acid fuel cells, protons move through the electrolyte to the cathode to combine with oxygen and electrons, producing water and heat. For alkaline, molten carbonate, and solid oxide fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons. The electrons from the anode side of the cell cannot pass through the electrolyte to the positively charged cathode; they must travel around it via an electrical circuit to reach the other side of the cell. This movement of electrons is an electrical current. Because there is no combustion, fuel cells give off few or no emissions; because there are no moving parts, fuel cells are quiet and reliable. Fuel cells can be used in stationary applications like generating electricity or heating buildings, and for powering vehicles, buses and trains.

Figure 2

Fuel Cell Concept



This section reviews six fuel cell types which are primarily being investigated. Among these, the proton exchange membrane fuel cell, (PEM), also referred to as the polymer electrolyte fuel cell (PEFC) is, with today's knowledge, one of the most promising technologies. This is the type of fuel cell that most experts believe will be the most efficient for powering cars and buses and even may be used for residential power applications. The Solid Oxide Fuel Cells (SOFC) appear to be the most promising technology for electric power plants. Combined with a gas turbine, SOFC s are expected to achieve an electric efficiency over 70 percent. The Direct Methanol Fuel Cell (DMFC) appears to be promising as a battery replacement for portable applications such cellular phones and laptop computers.

Fuel Cell Types

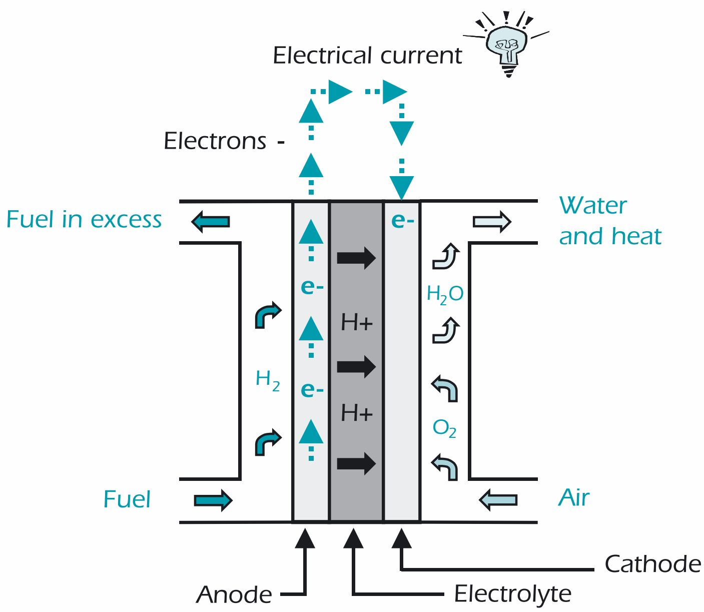
This section provides a brief description of the various, "leading" fuel cell technologies currently under development.

○ Polymer Electrolyte Membrane (PEM)

Polymer Electrolyte Membrane (PEM) fuel cells – also called Proton Exchange Membrane fuel cells or Polymer Electrolyte Fuel Cells (PEFC) – deliver high power density and offer the advantages of low weight and volume, compared to other fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. They need only hydrogen, oxygen from the air, and water to operate and do not require corrosive fluids like some fuel cells. They are typically fuelled with pure hydrogen supplied from storage tanks or onboard reformers.

Figure 3

PEM Fuel Cell



PEM fuel cells operate at relatively low temperatures, around 80°C. Low temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components, resulting in better durability. However, they require that a noble-metal catalyst (typically platinum) be used to separate the hydrogen's electrons and protons, adding to system cost. The platinum catalyst is also extremely sensitive to CO poisoning, making it necessary to employ an additional reactor to reduce CO in the fuel gas if the hydrogen is derived from an alcohol or hydrocarbon fuel. This also adds cost. Developers are currently exploring platinum/ruthenium catalysts that are more resistant to CO.

PEM fuel cells are used primarily for transportation applications and some stationary applications. Due to their fast start-up time, low sensitivity to orientation, and favourable power-to-weight ratio, PEM fuel cells are particularly suitable for use in passenger vehicles, such as cars and buses.

○ *Phosphoric Acid (PAFC)*

Phosphoric acid fuel cells (PAFC) use liquid phosphoric acid as an electrolyte – the acid is contained in a Teflon-bonded silicon carbide matrix – and porous carbon electrodes containing a platinum catalyst. The PAFC is considered the "first generation" of modern fuel cells. It is one of the most mature cell types, the first to be used commercially, and features the most proven track record in terms of commercial applications with over 200 units currently in use. This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

PAFCs are more tolerant of impurities in the reformate than PEM cells, which are easily "poisoned" by carbon monoxide – carbon monoxide binds to the platinum catalyst at the anode, decreasing the fuel cell's efficiency. They are 85 percent efficient when used for the co-generation of electricity and heat, but less efficient at generating electricity alone (37 to 42 percent). This is only slightly more efficient than combustion-based power plants. PAFCs are also less powerful than other fuel cells, given the same weight and volume. As a result, these fuel cells are typically large and heavy. PAFCs are also expensive. Like PEM fuel cells, PAFCs require an expensive platinum catalyst, which raises the cost of the fuel cell. A typical phosphoric acid fuel cell costs between $4,000 and $4,500 per kilowatt in investment costs. Although interest in the PAFC has faded, it currently plays a role in niche applications, e.g. for military purposes.

○ *Direct Methanol (DMFC)*

Most fuel cells are powered by hydrogen, which can be fed to the fuel cell system directly or can be generated within the fuel cell system by reforming hydrogen-rich fuels such as methanol, ethanol, and hydrocarbon fuels. Direct methanol fuel cells (DMFCs), however, are powered by pure methanol.

As such, DMFCs do not have many of the fuel storage problems typical of some fuel cells since methanol has a higher energy volume density than hydrogen – though less than gasoline or diesel fuel. Methanol is also easier to transport and supply to the public using our current infrastructure since it is a liquid, like gasoline.

Direct methanol fuel cell technology is relatively new compared to that of fuel cells powered by pure hydrogen, and research and development are roughly 3-4 years behind that of other fuel cell types. Nonetheless, the DMFC appears to be the most promising as a battery replacement for portable applications such cellular phones and laptop computers, and a number of manufacturers are already introducing commercial versions of these applications.

○ Alkaline (AFC)

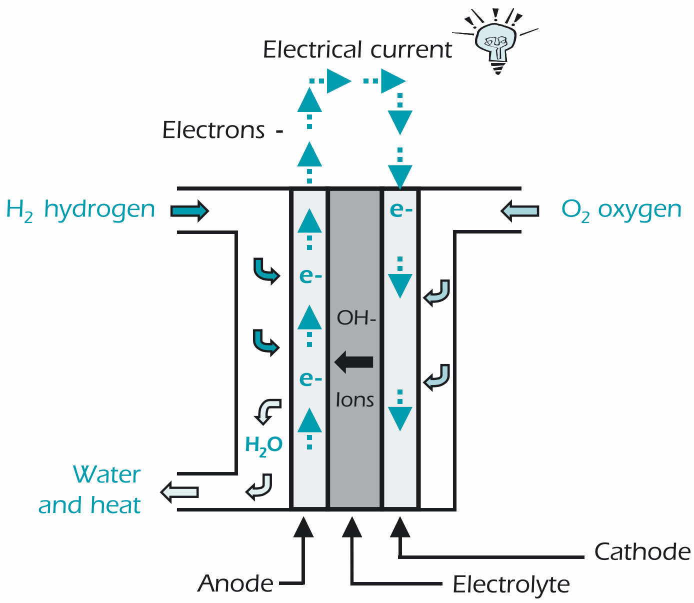
Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were the first type widely used in the US space program to produce electrical energy and water onboard spacecraft. These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. High-temperature AFCs operate at temperatures between 100°C and 250°C. However, more-recent AFC designs operate at lower temperatures of roughly 23°C to 70°C.

AFCs are high-performance fuel cells due to the rate at which chemical reactions take place in the cell. They are also very efficient, reaching efficiencies of 60 percent in space applications. The disadvantage of this fuel cell type is that it is easily poisoned by carbon dioxide (CO_2), which has limited interest in its commercialisation. In fact, even the small amount of CO_2 in the air can affect the cell's operation, making it necessary to purify both the hydrogen and oxygen used in the cell. This purification process is costly. Susceptibility to poisoning also affects the cell's lifetime, further adding to cost. Evidently, solutions involving CO_2 purification by means of regenerative adsorption is increasing the competitiveness of the AFC.

Cost is less of a factor for remote locations such as space or under the sea. However, to effectively compete in most mainstream commercial markets, these fuel cells will have to become more cost effective. AFC stacks have been shown to maintain sufficiently stable operation for more than 8,000 operating hours. To be economically viable in large-scale utility applications, these fuel cells need to reach operating times exceeding 40,000 hours. Along with the high vulnerability to CO_2 poisoning, this is possibly the most significant obstacle in commercializing this fuel cell technology.

Figure 4

Alkaline Fuel Cell



Molten Carbonate (MCFC)

Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminium oxide ($LiAlO_2$) matrix. Since they operate at extremely high temperatures of 650°C and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs.

Improved efficiency is another reason MCFCs offer significant cost reductions over phosphoric acid fuel cells. MCFCs can reach efficiencies approaching 60 percent, considerably higher than the 37-42 percent efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85 percent.

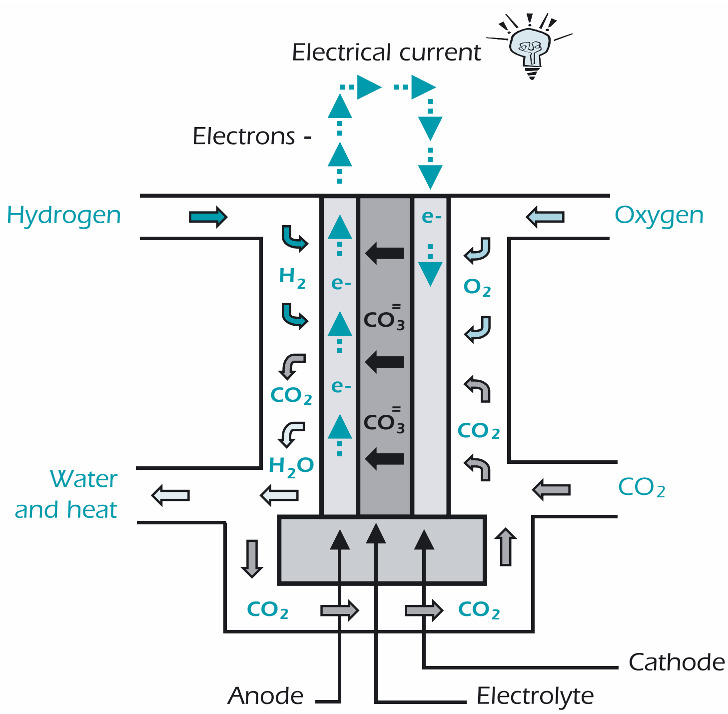
Unlike alkaline, phosphoric acid, and polymer electrolyte membrane fuel cells, MCFCs don't require an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which they operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.

Although they are more resistant to impurities than other fuel cell types, scientists are looking for ways to make MCFCs resistant enough to impurities from coal, such as sulphur and particulates.

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs that increase cell life without decreasing performance.

Figure 5

Molten Carbonate Fuel Cell



Solid Oxide (SOFC)

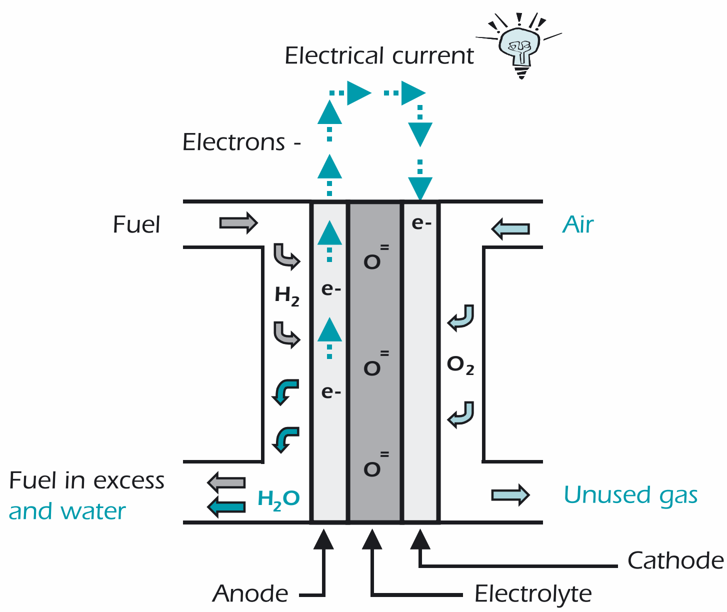
Solid oxide fuel cells (SOFC) use a hard, non-porous ceramic compound as the electrolyte. Since the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types. SOFCs are expected to be around 50-60 percent efficient at converting fuel to electricity, however, calculations show that over 70 percent may be achievable. In applications designed to capture and utilize the system's waste heat (co-generation), overall fuel use efficiencies could top 80-85 percent.

Solid oxide fuel cells operate at very high temperatures, around 1,000°C. High temperature operation removes the need for precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels internally, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system. SOFCs are also the most sulphur-resistant fuel cell type; they can tolerate several orders of magnitude more sulphur than other cell types. In addition, they are not poisoned by carbon monoxide (CO), which can even be used as fuel. This allows SOFCs to use gases made from coal.

High-temperature operation has disadvantages. It results in a slow start-up and requires significant thermal shielding to retain heat and protect personnel, which may be acceptable for utility applications but not for transportation and small portable applications. The high operating temperatures also place stringent durability requirements on materials. The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing this technology. Scientists are currently exploring the potential for developing lower-temperature SOFCs operating at or below 800°C that have fewer durability problems and cost less. Lower-temperature SOFCs produce less electrical power, however, and stack materials that will function in this lower temperature range have not been identified.

Figure 6

Solid Oxide Fuel Cell



Major programs on fuel cell technologies

Virtually all of the IEA governments participating in the survey reported work on fuel cell development, either as a specific project or part of a much broader RD&D program. Notably, several countries feature long-running, well-funded programs, which cut across all of the technologies and include sizeable demonstration projects for transportation and stationary fuel cell applications. These "major" programs are summarised below.

Japan arguably leads the world in fuel cell technology development. This has come about through sustained public and private investment in technology development over the past twenty years covering both low and high temperature fuel cell systems. The focus of R&D has changed over the years, with current efforts very much directed at commercialization of PEMs for transportation applications and as sources for embedded generation for domestic and office buildings. The Japan Hydrogen Fuel Cell (JHFC) Demonstration Project is possibly the most highly developed fuel cell and hydrogen demonstration in the IEA region, including stationary and automotive applications, and featuring integrated road test demonstrations of FCVs and the operation of hydrogen refuelling stations. Research and development include PEMs along with MCFCs and SOFCs.

Canada has a long-standing involvement in the development of hydrogen and fuel cell technologies, focusing on fuel cells for transportation and stationary power, including off-grid applications. Program activities are oriented toward the development of technologies with short-to-medium term commercial potential. The R&D program focuses on fuel cell commercialisation and the development of coordinated hydrogen and fuel cell standards that will be required for hydrogen to be a safe and cost-effective energy carrier. Canada is currently focusing on the development and demonstration of various PEM fuel cell technologies, along with developing DMFC for portable, stationary and automotive applications, and on fundamental and applied research to develop novel materials and architectures for high temperature fuel cells and micro fuel cells. The program is managed by Natural Resources Canada, National Research Council, Natural Sciences and Engineering Research Council, Department of National Defence and Environment Canada. The annual budget is approximately C$20M. These R&D activities are complemented by two demonstration programs which will invest C$83 million in hydrogen infrastructure and fuel cell product demonstrations.

Germany has conducted intensive R&D on fuel cells over the last 10 years, concentrating on new materials, improved components and system integration. The programme brings together national research centres, universities and industry partners. Fuel cells have become an option for broad application in stationary and automotive applications, reducing investment costs from €50,000/kW to €10,000/kW. The German fuel cell programme has received strong national funding and has made notable progress in a number of key areas including development of high temperature fuel cells for stationary applications; development of an MCFC system; tube concept for SOFC; planar SOFC concept; and development of a fuel cell system for house applications. Public funding through the Federal Ministry of Economics and Labour (BMWA) for fuel cell activities amounts to €8-10 million annually and combined with private sector support, this yearly amount reaches €16-20 million annually. Within the *Programme on Investment into the Future*, additional €15 million of public funding per year have been granted for fuel cell projects during the period 2001-2003. Basic research on fuel cells in the Helmholtz research centres is supported by the Federal Ministry of Research and Education which amounts to about €15 million per year. Within the Federal States fuel cell and hydrogen programs (Bavaria, North-Rhine-Westphalia, Baden-Württemberg and Saxony) approximately €20-25 million per year are being allocated.

France conducts its fuel cell programs through support by research institutes CEA and CNRS and in cooperation with French industrial companies, including Helion, Axane, Sagem, Renault, Peugeot Citroen, Paxitech, and Snecma. This effort is partially funded by the French PACo network at roughly €10 million per year with a major part of the research devoted to the understanding of degradation mechanisms and ageing in PEM fuels cells and the development of new membranes. Sulfonated Polysulfones have been extensively studied over the last few years and new hybrid membranes using inexpensive components such as composite and metallic bipolar plates and new catalysts (bi and tri metallic) with less platinum are under development. With respect to SOFCs, France has conducted intensive research on intermediate temperature (700°C) cells, internal reforming and new designs for high power stacks.

Italian R&D activities in fuel cell development started in the early 1980s. Currently, they are focused on the development and demonstration of PEMs for stationary and automotive applications and MCFCs for on-site and distributed generation. Moreover, some research activities on materials and components for SOFCs are being carried out. The national R&D program on *Hydrogen and Fuel Cells*, supported by the Ministry of Research and University and the Ministry of the Environment, has been outlined in the framework of the National Research Plan (PNR). On March 2003, the Ministry of Research launched a call for proposals on *New Systems for Energy Production and Management*. A three year budget of around €90 million is available for hydrogen and fuel cells technologies.

In the United States, the DOE leads a heavily-funded, wide-ranging program, working closely with its national laboratories, universities, other federal agencies and industry partners to overcome critical technical barriers to fuel cell commercialisation. Current R&D is focused on the development of reliable, low-cost, high-performance fuel cell system components for transportation and buildings applications. Fuel cell R&D responsibilities at DOE, include research on SOFC and MCFC with a FY 2003 funding of US$47 million, of which approximately $11.5 million is allocated towards the Vision 21 projects that develop clean central station generation technologies. The remainder is allocated to technologies that are more focused on distributed generation applications. A cornerstone activity is the Solid State Energy Conversion Alliance (SECA), a partnership between DOE, the National Laboratories, and industry to develop and demonstrate planar solid oxide fuel cells for distributed generation applications. DOE also develops fuel cell technologies with an emphasis on the PEM fuel cell for both stationary and transportation applications. The FreedomCAR partnership between DOE and USCAR (a pre-competitive research organisation consisting of General Motors, Ford and DaimlerChrysler) is the mechanism through which PEM fuel cells are being developed for use in automotive applications. DOE also has the responsibility for developing PEM fuel cells for portable and distributed generation applications as well as the technologies required for the hydrogen energy infrastructure that is important in the long-term for large scale use of PEM fuel cells. The FY 2003 budget allocation for the integrated DOE program was US$92 million, split between PEM fuel cell R&D ($52 million), and hydrogen production, infrastructure, and storage R&D ($40 million).

In addition to these major fuel cell programs, virtually all of the IEA governments participating in the HCG survey reported work on fuel cell development. Efforts were variously concentrated on the development of specific fuel cell technologies and on general R&D on fuel cell materials and components; and, most of the countries also operate demonstration programs which are aimed at testing, verifying and commercialising fuel cells in both transportation and stationary applications.

R&D efforts directed at specific fuel cell type

R&D on Polymer Electrolyte Membrane (PEM) fuel cells

The PEM fuel cells offers an order of magnitude higher power density than any other fuel cell system, with the exception of the advanced aerospace AFC. Recent advances in performance and design offer the possibility of lower cost than any other fuel cell system.

In Europe, Belgium R&D in the area of PEMs has concentrated on fuel cell design optimisation. Also, Belgium participates in the *Accept* program to develop PEM stacks fuelled by ammonia (via a reformer) for automotive use. In Finland, a free convection PEM fuel cell (10-100 W) for a portable computer application is under design, and a 1.5 kW PEM module for micro CHP (combined heat and power) is under construction. The *Fuel Cell Technological Research Network* (PACo Network) was created by the French government to contribute to the development of new energy sources. French fuel cell R&D activities are diverse, highly-developed and are concentrated on PEM technology (along with DMFC). France is also developing micro fuel cells (PEM) using hydrogen as a fuel from a hydrogen cartridge, with a innovative design based on Silicon micro technology processes (power density obtained 200 mW/cm^2 at 25°C). Italian R&D activities on fuel cells started in the early 1980s and are currently focused on the development and demonstration of various fuel cells technologies, particularly PEMs for stationary and automotive applications. Portugal's research focuses on low temperature PEMs, particularly new materials for components and testing of operating conditions. The work is carried out by the National Institute of Engineering, Technology and Innovation. Spain works in new materials, design with computational fluid dynamics, reduction of weight and volume, and increasing CO tolerance. Norway conducts specific R&D on PEMs at the NTNU in Trondheim. In Switzerland, the Paul Scherrer Institute started its R&D on PEM-Technology in the early 1990s, focussing on components (membranes, electrodes, catalysts), continued stack development, novel diagnostic tools for bipolar plates and stacks. In Germany, the development of PEM systems for stationary applications in the range of 2-5 kW is in an advanced stage. The main targets of this programme are the optimisation of the performance and decrease of the overall system costs. German car manufacturers are developing PEM for mobile applications (main power source as well as Auxiliary Power Units – APU). Several projects on portable use of PEM (up to 1 kW) are carried out. Greece also reports work on the development of high temperature membranes for PEMs.

The EU's "FURIM" program targets the development of novel PEM membranes and related components for high temperature fuel cells; and the testing of PEM stacks to evaluate their technical, economic and environmental impacts. Thirteen European partners are involved in the €4 million project. The EU's H_2-MINIPAC is focused on the development of micro PEM fuel cells using hydrogen as a fuel.

Since 1985, Canada has been one of the pioneers in the development of PEM technologies and applications. Largely through cost-shared agreements with the private sector, one of the most successful developments has been the Ballard PEM fuel cell – which is used in many of the fuel cell vehicles currently in demonstration/operation today.

In Japan, the focus of PEM work is now on reducing the manufacturing cost of PEM systems. METI and NEDO will continue R&D on fuel cells to meet performance targets, durability, and cost reductions toward future commercialisation, primarily focusing on R&D for relevant system and production technologies and components such as membrane, electrode, MEA and separators. Program elements

include development of PEM systems and components, the *Next Generation PEM System Project*, micro-PEM development, and engineering & safety standards for PEM systems. Since LP Gas is one of the major sources for the households in Japan, a project also focuses on using LP Gas for fuel cells. R&D will be conducted on fuel processing and evaluation of stationary PEM systems for LP Gas, including desulphurisation and fuel reforming.

The US DOE hydrogen, fuel cells technologies research and development activities are aimed at reducing fuel cell system cost and size and improving the performance and durability of fuel cell systems for transportation, small stationary, and portable applications. Most of this research focuses on advancing PEM fuel cell systems, with emphasis in areas such as fuel processing (reforming) technologies, improved catalyst and membrane designs, and improved air, thermal, and water management systems. The US activities focus on the PEMFC because of its low-temperature operation and capability for fast start up. RD&D program elements include "Cross Cutting PEM Stack and Fuel Processing R&D," which has a budget of US$40 million. DOE has a US $7.4 million program for developing PEMs for stationary applications and a US $7.5 million program for automotive applications. There is also US$9.9 million budgeted for demonstrating transportation PEM applications.

○ R&D on Phosphoric Acid (PAFC) fuel cells

Japan is the only country that reported substantive work on PAFCs, citing that the country's fuel cell R&D efforts were initially focused on PAFC (and high temperature MCFC) systems. PAFC was the first fuel cell to be commercialized in Japan. Led by Toshiba Corporation, Fuji Electric Co., Ltd., and Mitsubishi Electric Corporation, PAFCs with output of 50-200 kW have been installed in hotels, hospitals and supermarkets. Additionally, a number of beer breweries have installed co-generation facilities using methane gas from the beer brewing process to fuel PAFCs. Recently, however, Japan has taken a marked change in direction and has shifted the spotlight firmly onto PEM system development. In addition to Japan, Korea reported the installation and testing of a prototype 50 kW PAFC System.

○ R&D on Direct Methanol (DMFC) fuel cells

Several countries reported efforts to develop DMFCs, including general R&D in Belgium, Canada, Denmark, Portugal and Switzerland. Most of the work focuses on the use of DMFCs for portable and mobile/micro applications, such as the work being done by private/public start-ups in Austria. France is also developing innovative concepts by applying silicon micro-technologies processes for portable applications of the DMFC and Spain has a project to develop a 50W DMFC for portable applications. Germany conducts several projects on development of DMFC, including R&D on new membranes. Some German industrial firms already offer first prototypes for portable and micro applications.

Micro fuel cells are an area of key interest to Japan's electronic firms, especially as power sources for portable appliances. In terms of technology trends, most firms have settled on using methanol as the fuel source because it can be used directly in a DMFC. On balance, DMFC systems are attracting considerable attention, although issues such as methanol crossover, water management and poor catalyst performance are hindering commercialisation. In order to overcome some of these barriers, the Japanese government has initiated a program for R&D in this area from FY 2003 onwards. One program element focuses on developing DMFCs to generate electricity for mobile equipment such as mobile phones, electronic terminals, and mobile power supplies. The project

covers R&D on components, manufacturing system and evaluation, and is supported by a 2003 budget of ¥2.2 billion. Korea is developing a 100 W DMFC system, with industrial participants including LG Chemical Co and LG Electronics Co.

○ R&D on Alkaline (AFC) fuel cells

Austria, Belgium and Finland reported work on AFCs. During the 1990s the Austrian program included an element for AFC R&D, though these activities have been largely discontinued. As early as 1976, Belgium was conducting R&D on AFC, but this work has also been discontinued – and again restarted by E-Vision company. Notably, in Finland, the AFC has successively been integrated and tested in a boat (200 W) and in a small scale electric vehicle application (1 kW).

○ R&D on Molten Carbonate (MCFC) fuel cells

MCFCs promise high fuel-to-electricity efficiencies, about 60% normally or 85% with cogeneration, and 10 kW to 2 MW MCFCs have been tested on a variety of fuels. MCFCs are primarily targeted to electric utility applications and they have been successfully demonstrated in Japan and Italy.

In Europe, a number of countries are developing MCFC technologies. Denmark, Germany and Italy all report the development of MCFC systems, primarily for stationary central or distributed power generation. The German activities on MCFC systems based on the so called "Hot Module System" are in the very advanced state. At present, within the national "Program on Investment into the Future" (ZIP), six 250 kW MCFC units operate under real conditions at customers' sites. Changes of the cell design are expected to simplify the production process, promising further cost reduction. The main R&D efforts for reaching these goals are new sealing concepts; new processes allowing series production; high temperature, corrosion resistant metallic materials; developments of sub-systems like inverters, fuel reforming, pumps etc. Austria and Spain are working on a biogas-fuelled MCFC in cooperation with Germany. And the Turkish Marmara Research Centre is developing a 500 kW MCFC power plant.

The University of Queensland in Australia conducts general R&D to support MCFC systems as part of a project to develop advanced system integration techniques and catalysts for internal reforming fuels cells. The aim is to enable a wide range of fuels to be used with MCFCs for small scale stationary applications suitable for remote areas in Australia.

Korea's extensive work across all the fuel cell types has MCFC as the major focus, accounting for 50% of the R&D funding. Korea is developing a 100 kW MCFC with industrial participants, including KEPRI, Hyosung Heavy Ind., and Samsung. There is also a project for commercialising a 250 kW MCFC CHP prototype plant by 2008.

Japanese government and industry are active in developing high-temperature fuel cells. MCFC system development has been ongoing since 1981 with an R&D focus on high-performance and high-pressure stack technologies as the basis for power generation and co-generation. This work has reached an advanced level and features the involvement of electric power utilities and heavy industrial firms. In Japan, the NEDO has shifted the focus from large-scale system development to developing compact-sized modular systems that can be produced at low cost. The target markets are embedded power generation for factories, office buildings and major public facilities, as well as retrofitting ageing thermal power stations. System maker IHI has installed and commissioned

an external-reforming, pressurized 300-kW class MCFC system at Chubu Power's Kawagoe plant, in addition to installing its first commercial unit at their Shin-Nagoya plant. The former system will be used for durability trials, while the latter will be connected to a waste gasifier to demonstrate efficient power generation from refuse. The ultimate goal is to develop a compact, high-performance 750-kW system based on the MCFC, which will be comprised of 2 pressurized modules with an overall efficiency of 47%. The detailed design of the 750 kW system has also been completed and construction will commence during the latter half of this year. In addition, IHI has previously installed a 1,000 kW system during the second phase of this project, which ran for a total duration of 4,200 hours. It should be noted that given the mature level of MCFC technology NEDO has no current plans to continue this R&D program beyond FY 2004.

○ *R&D on Solid Oxide (SOFC) fuel cells*

SOFCs are another highly promising fuels cell that could be successfully applied to industrial and large-scale central electricity generating stations. Some developers also see SOFC use in motor vehicles and are developing auxiliary power units (APUs) with SOFCs. Power generating efficiencies for 100 kW units could reach 60% and 85% with cogeneration. Demonstrations of tubular SOFC technology have produced as much as 220 kW. Japan has two 25 kW units online and a 100 kW plant being testing in Europe.

The Australian company Ceramic Fuel Cells Limited (CFCL), a leader in planar SOFCs, is seeking to identify potential partners to create market-ready packages that would incorporate solid oxide fuel cells.

In Europe, Austria has developed a 1 kW SOFC based on natural gas fuel cells. Denmark reports progress on five SOFC projects, and the Danish fuel cell strategy is oriented towards small SOFC stationary power systems. There is also some interest in using SOFC in other application areas such as auxiliary power units. In the Netherlands, research on SOFC started in 1990 for CHP applications with natural gas. Norway has also concentrated on improving the working efficiency and competitiveness of SOFC fuel cells for power generation with natural gas. One aspect of this work includes R&D on filter mechanisms for cleaning hydrogen from gasified biomass to reach sufficient purity. In Spain, Ikerlan Company has undertaken the *Mini Electricity Generation* project for the development of 1-2 kW SOFCs for application in distributed generation; and the Inasmet Foundation develops advanced thermal spray techniques to make cost effective and high quality planar SOFC. Half of Switzerland's fuel cell work has focused on SOFC, with a strong emphasis on market development of the Sulzer Hexis SOFC concept – which is believed to be close to market introduction. Basic R&D occurs at EMPA, ETH-Lausanne and ETH-Zurich, the latter with a strong focus on miniaturized SOFC for small portable applications such as cellular phones. As a spin-off of ETH-Lausanne, HTceramix SA will begin manufacturing stacks in 2005. Germany has developed both tube and planar concepts for SOFC, including the development and demonstration of 250 kW block power plants and demonstration of the SOFC tube concept in block power plants. Siemens Westinghouse develops High Power Density SOFC tubes with improved performance. These could open up the tubular technology to small scale applications (2-5 kW), for example, to combined production of heat and power for households. The planar SOFC concept developed at the Jülich and DLR Research Centres is being adopted as an auxiliary power unit (APU) for mobile applications by BMW and partners. French R&D in the area of SOFCs is focused on the development of materials and component stacks, including membranes and bipolar plates and internal reforming of methane. French companies (Snecma, Dalkia) and the CEA research institute are also developing a 5 kW stack for cogeneration applications. Italy concentrates SOFC research activities on materials, components and small stacks.

The European Union sponsors the *Real SOFC* program, which aims to raise the durability of p lanar SOFC stacks to a level acceptable for stationary applications; to find materials, manufacturing routes and standards suitable for low cost production; and, to reduce specific weight and volume of SOFC stacks. The consortium includes 25 of Europe's leading research and industrial organisations.

Japan continues to invest in high temperature SOFCs for large-scale power generation applications and the program focuses R&D on module cost reduction and reliability verification. SOFC systems are nearing commercialisation level, however a number of technical hurdles especially cell durability have yet to be resolved. One major objective in this area is to lower the operating temperature of SOFC systems to around the 750-800°C range. From an engineering viewpoint, realisation of this objective allows a wider range of materials selection including use of metals as electrodes and interconnects. Current technologies employ ceramics for these components, which suffer from thermal expansion, relatively poor electrical conductivity and durability issues. NEDO's program on SOFC development is also targeted at developing modular stack technologies that require no external heating. This modular construction is a key factor in reducing production cost and self-sustaining systems are both more compact and efficient. In this area, a partnership between Mitsubishi Heavy Industries and Chubu Power has built a 15 kW prototype system using planar cells. The system has been commissioned and, based on its success, both companies are in the process of developing a commercial 50 kW system.

Canada also reports industry capabilities in the production of 5-20 kW SOFCs. Residential and commercial applications are being demonstrated in Europe, the US and in cold weather climates including Alaska. Canada's research efforts are focused on developing "noval-nano" based materials and noval architecture to enable lower temperature, direct fuel, SOFC operation.

Fuel Cells: Basic R&D

○ Australia

Considerable work in the area of general research on fuel cells, materials and components was reported by Australia, where, assisted by government funding, efficiency improvements have been achieved in the operation of fuel cell electrodes by the formation of platinum nano-clusters in porous carbon by high density plasma sputter mechanisms. Initial experiments on the plasma sputter deposition of platinum onto a porous film have shown great promise. Aggregates of platinum were detected in the film with a density profile which decreased away from the surface exposed to the plasma. Australia's PEM work also concentrates on improving ceramic membranes formed from molecular sieve silicate materials, which feature 3 Å pore average, ideal for hydrogen separation from other gases such as CO_2, CO, and N_2. These membranes can operate at high temperatures up to 400-500°C. The work focuses on the preparation of materials using sol gel methods. Additionally, general R&D in Australia looks at developing materials consisting of composite inorganic and organic polymers. The inorganic component consists of proton conducting materials such as zirconium phosphate. The organic polymer consists of proton-conducting materials such as Dupont's Nafion. The aim is to develop material that has high sustained proton conductivity at high temperatures, thereby reducing the requirement for CO removal from hydrogen fuel and making the PEM fuel cell system more robust.

Europe

Austria reports work on reformer and component development of fuel cell systems fuelled by renewable energy sources, including biogas, solid biomass, and PV. Austria's CD Laboratory also engages in basic R&D on circulating electrolytes. The Belgian program activities include miniaturisation and integration of a hydrogen generator with a fuel cell, and the application of nano-compounds to the design of fuel cell membranes under the *Nanocell Program*. In France, general R&D efforts deal with fuel-related issues for fuel cells through the development of small reformers for on-board hydrogen production. Many new membranes are under development at CNRS and CEA, including fluorinated membranes, non-fluorinated membranes, and hybrid membranes (organics/inorganics). New materials for bipolar plates are also being developed, and new design and tests for PEM stack are in progress in France. Several Italian research organizations (ENEA, CNR, CRF, and several universities) and industries (Nuvera Fuel Cells Europe, Arcotronics Fuel Cells, IVECO) are working on R&D of materials, components, cells, stacks and systems. In Norway, the country's main effort during the last 5-10 years has been related to fundamental and basic R&D on material science, especially membranes for fuel cells and catalysts for PEMs. The major objectives are to develop alternative catalysts or processes reducing the use of platinum. Spain has been active in fuel cell research since the early 1990s, focusing efforts on the development of materials for MCFCs and PEMs. The Spanish CIEMAT and INTA developed capabilities to test fuel cell stacks and components for AFCs, PEMs, PAFCs and MCFCs. Work is in progress in the fields of catalysts application, new developments for membranes, electrolytes and PEMs. Fuel cell design with numeric simulation has been done utilising a computational fluid mechanics program and experimental validation of a 2.5 kW PEM. Portugal has been focussing on the development of laboratory and experimental models of power sources using PEM fuel cells – achieving a power output of 5 W to 1 kW, by the INETI and INEGI research centres. Other work includes a contract with a Portuguese company aimed at commercialisation aspects of the PEM work. The Portuguese Foundation of Science and Technology is responsible for financing national projects, namely on mathematical modelling applied to DMFC, carried out by the University of Oporto and at the research Institute INETI.

In Germany, basic R&D is carried out with the goal of finding new materials for cells and stacks (SOFC, MCFC, PEM and DMFC), development of new membranes (PEM and DMFC), electrodes and new catalysts. The main players are research centres DLR, Jülich, Fraunhofer and several universities. It can be noted that Denmark is concentrating on the development of high-temperature membranes. In Sweden, four different PAFCs were tested during the 1990s. All these demonstration plants have now been terminated. However, during 2004, a number of fuel cell installations have been effective in Stockholm – all residential with the aim of demonstrating new technologies in new buildings. The UK has a very strong portfolio of programs supporting fundamental R&D and industrial RD&D. National support is delivered by the UK Engineering and Physical Sciences Research Council, the UK Department of Trade and Industry, and the UK Carbon Trust. The UK DTI's *New and Renewable Energy Program* has supported a total of 156 projects, with a focus on SOFC and PEM cells.

Japan

Japan work aimed at fundamental R&D for fuel cell development – basic research to achieve drastic upgrades in materials and components – is conducted by national institutes (e.g. the National Institute of Advanced Industrial Science and Technology). The budget allocations for 2001-2003 total ¥1.8 billion; the 2003 allocation is ¥726 million.

Korea

An R&D program for developing basic technologies was formulated in June 2004. This program consists of four parts: fundamental technology development for PEM, SOFC, DMFC, and next generation fuel cell technology. Eliminating barriers to commercialisation of fuel cells such as lifetime, reliability and cost are the main targets of the program. It is scheduled to continue from 2004 to 2011 with a budget of US$40 million.

North America

Primarily focused on the PEM, Canada conducts various general R&D programs on reliability, materials costs, noval electro-catalysts, manufacturing direct fuels, sensors and diagnostics, enhanced performance materials and novel architecture. The work also investigates new membranes for higher operating temperatures, lower manufacturing costs for MEAs and bipolar plates with effective sealing systems, as well as novel micro systems for portable applications.

The US reports that the development of new materials for improved fuel cell stack and system and for lower cost is central to achieving objectives of the DOE HFC effort. Work is ongoing in universities, national laboratories, and within industry to identify new materials and fabrication methods for fuel cell membranes, catalysts, and bipolar plates; and to integrate these new materials and methods into fuel cells for testing. Development of enabling technologies has been a success story for the DOE's Office of Energy Efficiency and Renewable Energy, where the program is progressing by: developing new membranes for operation at temperatures up to 120°C for improved thermal management and impurity tolerance; developing advanced catalyst-coated membranes; developing highly-conductive, gas-impermeable bipolar plates and fabrication processes; minimising precious-metal loading; and, assessing and improving component durability.

The US notes that some of the technologies developed for stationary fuel cell applications such as low-cost, compact fuel processors could also be used for off-board processing of fuels to produce hydrogen at vehicle refuelling stations. Thus, the program includes R&D on quick start-up reformers. Ongoing research in industry and national laboratories will focus on improved catalysts and engineering efforts aimed at improving the thermal properties of the fuel processor. Objectives for the general fuel cell R&D in the US include:

- Develop a 60% efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $45/kW (including hydrogen storage) by 2010 and $30/kW by 2015.
- Develop a 45% efficient reformer-based fuel cell power system for transportation operating on clean hydrocarbon or alcohol-based fuel that meets emissions standards, a start up time of 30 seconds, and a projected manufactured cost of $45/kW by 2010 and $30/kW by 2015.
- Develop a distributed generation PEM fuel cell system operating on natural gas or propane that achieves 40% electrical efficiency and 40,000 hours durability at $400-$750/kW by 2010.
- Develop a fuel cell system for consumer electronics with proper energy density by 2010.
- Develop a fuel cell system for auxiliary power units (3-30 kW) with a specific power of 150 W/kg and a power density of 170 W/L by 2010.

Transportation fuel cell demonstrations

Overview

During the past decade, the fuel cell has risen in prominence as a clean, efficient and sustainable option for powering motor vehicles. In particular, PEM fuel cells have emerged as a potential replacement for the conventional internal combustion engine (ICE). A hydrogen Fuel Cell Vehicle (FCV) is engineered very much like a hybrid electric vehicle, however the electric motor is paired with a fuel cell generating the electricity in the place of the ICE. A fuel cell power system has many components, but its heart is the fuel cell stack where the combined electrical output of the fuel cells in the stack is sufficient to power the vehicle. The fuel cell stack in combination with the ancillary components of the FCV contribute to the long range, power density, and short refuelling time characteristics comparable to or even better than a conventional vehicle. Fuel cells are efficient, quiet, and have no moving parts. FCVs can be fuelled with pure hydrogen gas stored onboard in high-pressure tanks. Or, they can be fuelled with hydrogen-rich fuels – such as alcohol, natural gas, or even gasoline – although these fuels must first be converted into hydrogen gas by a device called a "reformer." Tailpipe emissions range from nothing but heat and water if hydrogen is used as the fuel, to some CO_2 and trace quantities of other regulated emissions if other fuels are used in combination with on-board reforming.

Fuel cells have moved remarkably quickly from laboratory to road testing. The City of Los Angeles, California, USA, recently leased the first of five Honda FCX models as part of a demonstration program designed to generate real road data. And, DaimlerChrysler is currently testing 60 Mercedes-Benz "F-Cell" A-Class fuel cell vehicles with demonstration partners under everyday conditions.

A number of the major automakers have stated their intention to begin selling – or expanding sales of – fuel cell passenger vehicles. Toyota plans to offer about 20 hybrid fuel cell SUVs based on its Highlander platform. Nissan has announced plans to start selling a fuel cell vehicle, and Ford Motor Company said it would offer a fuel cell version of the Focus in low-volume production for small fleet operations. Other FCVs include the GM Opel HydroGen 3, the Hyundai Santa Fe FCEV, and the Nissan Xterra FCV, the DaimlerChrysler Necar 5, and Daihatsu's Move FCV-K-2.

Predictions vary widely on the timing and penetration of FCVs into the passenger vehicle fleet market. Automakers for the most part are predicting sometime after 2010, with the market requiring at least 5 to 8 years to develop after the introduction of the first commercial vehicle. Projections for the US have indicated that fuel cells could achieve about 7-10 percent of the light duty vehicle stock by 2030, if current technical targets are met.

Another important area is the use auxiliary power systems (APU), which are expected to be one of the first niche applications for fuel cells in the transport area. Auxiliary power today represents a significant portion of the power needs for transportation. Developments of APUs may also have an impact in the stationary area.

Despite these amazing developments, time is still needed to prove and demonstrate low-cost, easy-to-manufacture designs and ancillary systems. It is expected that it will take several production cycles at low-to-medium volumes to gain experience, establish reliability, and achieve maturity. Over the next decade, automakers may be unwilling to commit to extensive production, since early designs could become obsolete before costs are fully recovered. The following section describes current

activities taken by IEA governments in the continued development of fuel cells for transportation applications and the various demonstration projects which are currently underway.

Europe

A number of European countries reported participation in a wide variety of EU-sponsored transportation demonstration programs. These include:

- **ELEDRIVE** is an EU thematic network program which focuses on fuel cell applications in electric and hybrid vehicles. The program started in December 2000 and ran for 3 years. Objectives were to create synergies between European countries in order to help select the most promising options for prototype bench- and field-testing of components and/or complete vehicles. The program also hoped to facilitate the exchange of experience and the transfer of knowledge with the aim to ensure a global discussion ensuring a complete overview of the different problems so as to foster R&D.

- **HYTRAN** is a program for developing and integrating components and sub-systems into a direct H_2 PEM power-train (80 kW) and APU Diesel re-formulate PEM (10 kW). The research consortium includes about 20 partners including the EU-wide car industry.

- **CUTE** is the *Clean Urban Transport for Europe* program, a pan-European demonstration project to support nine cities in introducing hydrogen into their public transportation system. The major objectives of the CUTE project are: (1) demonstration of 27 fuel cell powered regular service buses produced by Daimler Chrysler over a period of two years in nine European cities to illustrate fuel cell performance within the large spectrum of different operating conditions to be found in Europe; (2) design, construction and operation of the necessary infrastructure for hydrogen production and refuelling stations. To date, nine hydrogen fuelling stations have been constructed; and (3) collection of findings concerning safety, standardization and operating behaviour of production for mobile and stationary use, and exchange of experiences including bus operations under differing conditions among the numerous participating companies for replication and ecological, technical and economical analysis of the entire life cycle; (4) quantification of the abatement of CO_2 at European level and contribution to commitments under the Kyoto Protocol. The EC has allocated €18.5 million to CUTE for programme implementation in the following cities: Amsterdam (Netherlands), Barcelona (Spain), Hamburg (Germany), London (United Kingdom), Luxembourg (Luxemburg), Madrid (Spain), Porto (Portugal), Stockholm (Sweden) and Stuttgart (Germany).

- **ZERO REGIO** is a program for the development and demonstration of infrastructure systems for hydrogen as an alternative motor fuel, with the overall objective of developing low-emission transport systems for European cities. The specific objectives of the ZERO REGIO project are: (1) use of hydrogen (as an alternative motor fuel) produced as primary or waste stream in a chemical plant or alternatively through small "on-site" production facilities; (2) development of infrastructure systems for hydrogen consisting of hydrogen production, compression, storage and distribution equipment, and integration of these in conventional refuelling stations; (3) adaptation and demonstration of 700 bar refuelling technology for hydrogen; (4) demonstration of hydrogen as an alternative fuel via automobile-fleet field tests at two different urban locations in the EU (Rhine-Main, Germany, and Lombardia, Italy). Car fleets will be delivered and implemented by the automobile manufacturers Opel and Fiat. Field tests with the low-emission vehicles will be performed by respective city transport authorities and the airport authority in the Rhine-Main region.

A number of European countries also feature their own fuel cell demonstration programs:

- **Austria** – the *Austrian Advanced Automotive Applications*, or A3 program, includes PEM and hybrid vehicle demonstrations, environmentally-friendly urban bus, and product delivery traffic systems.

- **Germany** – within the "ZIP" program, four projects are underway for developing hydrogen-fuel cell buses and fuelling stations. Several fuel cell cars and one hydrogen fuelling station are demonstrated in the *Clean Energy Partnership* project in Berlin. Audi demonstrates a fuel cell powered A2-car. Also, under the EU project *Fuel Cell Buses for Berlin, Copenhagen, and Lisbon*, the Berlin Senate coordinates the demonstration and funding of a public transport bus equipped with a Nuvera fuel cell. Under the EU *CUTE* project the demonstration of hydrogen infrastructure for the DaimlerChrysler fuel cell bus NEBUS/Citaro is being co-financed within ZIP. BMW together with seven industry partners develops SOFC-based APU for passenger cars. Projects for the demonstration of fuel cell buses (Stadt Barth, Berlin) and the development of a fuel cell car (Audi) are also included. Additionally, MAN has partnered with Ballard to develop a 40-foot fuel cell bus for demonstration at the Munich Airport, beginning in 2004.

- **Italy** – the first hydrogen-powered urban fuel cell bus was developed by Iveco/Irisbus for the municipal transport authority of Turin in 2001. The bus, in hybrid configuration, is fuelled with hydrogen (electrolysis) and equipped with a battery system. The fuel cell is supplied by International Fuel Cells and has a power rating of 60 kW.

- **Portugal** – implemented a €4 million project financed by the National Program PEDIP II, directed towards the implementation of an infrastructure for the research and demonstration of low temperature PEMs and new materials for components. This project also aimed at inducing commercialisation in the industrial sector by disseminating emerging technologies, validating components and demonstrating a prototype of a fuel cell.

- **Spain** – is active in developing demonstration projects for hydrogen infrastructure and fuel cells. The most important market introduction initiatives have been taken by Madrid and Barcelona urban transport authorities, which manage the demonstration of buses running on hydrogen in Madrid and Barcelona streets (CUTE). As a part of the *Technical Investigation Promotion Program*, supported by the government, a private public consortium coordinated by Irisbus Spain has invested over €4 million in the development and construction of a hybrid urban bus for Madrid with hydrogen fuel cell and batteries as auxiliary power. Two of the first hydrogen refuelling stations in Europe were built in Madrid, by the consortium of Repsol YPF, Air Liquide Spain and Gas Natural Company; and in Barcelona, sponsored by BP. Hydrogen is produced in the Madrid station with on site natural gas reforming and in Barcelona through electrolysis, with 10 percent of the electricity provided by photovoltaic power.

- **Sweden** – participates in the CUTE-program. In addition, the government funded MISTRA program, along with participation from Volvo, has been an important program for developing fuel cell power systems in vehicles.

- **Switzerland** – the Paul Scherrer Institute demonstrated its PEM technology in combination with supercaps, first in a VW Bresa (January 2002) and later in a car with improved performance (October 2004).

- **UK** – with support from the UK Energy Savings Trust and the Greater London Authority, three fuel cell buses operating on hydrogen are being demonstrated in central London as part of the EU CUTE program. The UK also has a strong program of industrial R&D, developing PEM fuel cell technology for transport applications. The UK Department of Trade and Industry is providing £3.6 million to a consortium led by Intelligent Energy to develop an advanced 50 kW PEM stack (total project cost £5.1 million). It has also recently awarded a grant of £3.7 million to a consortium led by Johnson Matthey to develop lower cost automotive class membrane electrode assemblies (MEAs) for PEM fuel cells (total project cost £6 million).

Japan

Of the surveyed countries, Japan has one of the most highly developed fuel cell and hydrogen demonstration programs for transportation (and stationary) applications: The *Japan Hydrogen Fuel Cell Demonstration Project* (JHFC) consists of road test demonstrations of FCVs and the operation of hydrogen refuelling stations. These stations are being operated and evaluated along with the FCVs that participate in this project. Moreover, forty-eight FCVs and five fuel cell buses from domestic and overseas car manufacturers are participating in this project and various data such as drivability, environmental characteristics, and fuel consumption will be obtained for evaluation. Major components of this project also include the construction of ten hydrogen stations around Tokyo (now completed).

Japan also has a focused lithium-ion battery R&D project for FCVs in order to complement fuel cell development and to advance efficiencies of FCVs. This project focuses on the commercialization of high-efficiency and high-power rechargeable lithium-ion batteries.

Korea

Korea launched a very aggressive RD&D program in 2004 to commercialize FCVs in the near future. The program covers basic R&D for break-through technology development and demonstration of FCVs in combination with an hydrogen refuelling station. The total budget for this program is US$60 million from 2004 to 2008. In addition to the domestic effort, Korean car maker Hyundai Motor Company has been active in the worldwide effort to develop and commercialise FCVs since 1997, working with many partners which have excellent technologies including UTC Fuel Cells. Hyundai became a Steering Member of the *California Fuel Cell Partnership* in June 2000, and unveiled its first hydrogen FCV, "Santa Fe FCEV," powered by UTC Fuel Cells' 75 kW fuel cell system in November 2001. Hyundai is now operating three Santa Fe FCVs on roads in California. During the demonstration, fuel cell technology is being investigated in real, everyday operation to identify further improvement in performance and safety, to understand infrastructure requirements and to establish a commercialisation strategy.

Australia

A demonstration trial of three hydrogen fuel cell-powered buses will commence in Perth, capital of Western Australia in September 2004. The trial is linked to the *European Integrated Hydrogen Project* which is evaluating the potential for the future operation of a hydrogen powered fuel cell public transport bus system. The program is funded at A$10.72 million. In addition, the University of Queensland is developing the "ultra-commuter," an ultra light-weight, low-polluting, series hybrid electric commuter vehicle suitable for Australian driving conditions. It will be partially powered by on-board solar cells, and a small scale (~ 10 kW) PEM.

North America

Canada has a long history of hydrogen and fuel cell demonstrations. In 1993, the world's first fuel cell bus was displayed and in 1996, a second generation bus was demonstrated. With the success of these first fuel cell buses, a bus fleet demonstration was launched in 1997 which integrated numerous HFC technologies and illustrated that fuel cells and ancillary components could function as a whole system. Highlights include:

- World's 1st Fuel Cell Bus: 1993 20-passenger 120 kW Ballard fuel cell engine, 160 km range.
- 2nd Generation Bus in 1996, world's 1st 40ft fuel cell bus, 205 kW Ballard fuel cell engine, 400 km range.
- Chicago/Vancouver Demo: 1st fleet demonstration program: 205 kW Ballard fuel cell engine with regenerative braking.

The Canadian *Transportation Fuel Cell Alliance* initiative focuses on demonstrating different combinations of fuels and fuelling systems for light, medium and heavy duty vehicles. Moreover, the *Fuel Cell Vehicle Demonstration project* will demonstrate the third generation Ford fuel cell Focus light-duty vehicles. Five vehicles will operate in Vancouver beginning in 2004. The project is managed by Fuel Cells Canada and funded by Natural Resources Canada, the government of British Columbia and the National Research Council. Results of the demonstration project will be used to influence future technology development. The project is to run for three years under C$5.8 million in funding.

Canada's hydrogen transport and distribution infrastructure program comprises refuelling stations (various locations and various companies), and includes work on large-scale water electrolysers, hydrogen compressors up to 700 bar, hydrogen dispensers, controls, and codes and standards.

Canada also reports that PEM fuel cells are being developed for off-road applications like utility vehicles, warehouse lift trucks and forklifts, ice resurfacing machines, and mining equipment. Demonstration of these applications are likely to be supported under the *Hydrogen Early Adopters Program*, a C$50 million program intended to showcase working models of the hydrogen economy through integrated demonstration projects undertaken in partnerships. Notably, Canadian HFC products around the world include Ballard Fuel Cells, which have been used in applications such as the Mercedes Benz Citaro Bus for the European CUTE program, and Dynetek Industries' on-board hydrogen fuel storage systems, which are also used in the CUTE program and in vehicles developed by DaimlerChrysler, Ford, Nissan, and MAN.

In the United States, the 2008 goal is to validate hydrogen fuel cell vehicles, which have greater than a 300-mile range, 2,000-hour fuel cell durability. The Bush Administration has pledged US$0.5 billion funding for the *FreedomCAR* initiative, a partnership between the U.S. Council for Automotive Research and the DOE. The goal of *FreedomCAR* is fundamental and dramatic: the development of emission– and petroleum-free cars and light trucks. *FreedomCAR* focuses on the high-risk research needed to develop the necessary technologies, such as fuel cells and advanced hybrid propulsion systems, to provide a full range of affordable cars and light trucks that are free of foreign oil and harmful emissions – and that do not sacrifice freedom of mobility and freedom of vehicle choice. One objective is to achieve 60% peak energy-efficient, durable fuel cell power systems (including hydrogen storage) that achieve a power density of 325 W/kg and operate on hydrogen. Cost targets are $45/kW by 2010 and $30/kW by 2015.

In California, USA, the *California Fuel Cell Partnership* (CaFCP) represents a large-scale collaboration between major energy and technology providers and local government authorities, with the overall objective to facilitate the path to fuel cell commercialisation by enhancing public awareness through vehicle and fuelling infrastructure demonstrations. The program currently includes 55 fuel cell cars, 2 fuel cell buses, and 3 hydrogen fuelling stations. Events organized under the auspices of the CaFCP, including technology forums and road rallies, have reached roughly 700,000 people, increasing overall awareness to 40% of California's population. A major goal of the partnership is to place 300 fuel cell cars and buses in fleets by 2005. The CaFCP will also continue to work on developing simple inter-operability procedures for FCV/fueling station interaction, which is crucial to ensuring safe and consistent future infrastructure.

Stationary fuel cell demonstrations

Overview

In addition to transportation applications, fuel cells could potentially produce electricity for homes, businesses and industry through stationary power plants. Sizes currently under development range from 1 kilowatt to several megawatts. Although stationary systems might penetrate the market even before FCVs, they will still face a difficult path to commercialisation. The major impediment is cost, especially since fuel cell stacks are still not well-suited to mass production techniques and in addition contain significant quantities of expensive noble metal catalyst. In terms of unit of energy cost, stationary fuel cell applications will largely be for applications that require heat as well as power (CHP). In the near term, it is expected that stationary fuel cell applications will likely be used for auxiliary power units (APU), distributed generation and generally to alleviate power draw from the grid rather than replace it.

Europe

- **Austria** – a key area of the country's R&D program includes deploying and demonstrating residential fuel cell systems (PEM and SOFC) in the near-term. Experience has also been gained with the demonstration of 200 kW PAFC power plants. Additionally, the Austrian gas industry has an initiative for testing fuel cell heating systems for residential applications using five residential fuel cell systems from Sulzer Hexis AG (Switzerland) and Vaillant Company (Germany). Depending on the results of these demonstration projects and the capabilities of the fuel cell system providers, major market deployment/implementation activities are expected.

- **Belgium** – the Sart Tilman Project demonstrates a Ballard PEM 220 kW stationary fuel cell.

- **Denmark** – reports a number of fuel cell demonstration projects, including: (1) the *PSO-Elkraft Project*, which is based on the Danish-developed SOFC. So far the facilities for long term testing have been built and the first tests are underway. Some lifetime factors have been identified and a new generation of cells have been developed with improved lifetime performance; (2) the *CORE-SOFC Project* to improve the durability of SOFC systems will focus mainly on materials selection for interconnects, contact layers and protective coatings to minimise corrosion between metallic and ceramic parts to achieve reliable and thermally-cyclable SOFCs. Degradation mechanisms will be identified and solutions will be developed and tested. In addition to typical operational conditions, the limits of performance under

high power density and during thermal cycling will be investigated. Especially for the anode compartment, the use of different fuel gases and utilisation will be of special concern by observing resulting corrosion effects on the interconnect surface under these operating conditions; (3) the *European Multi-Functional SOFC Project* (MF-SOFC) is a scale-up of a multi-functional SOFC to multi-tens of kilowatt levels. This program aims to develop a new generation of affordable indigenous European MF-SOFCs, built from an universal MF-SOFC module fabricated by inexpensive processes. It serves both sub-MW standalone combined heat and power, and multi-MW combined SOFC/gas turbine cycle systems; (4) the *EFP Project* is an SOFC project comprised of two parts. The first part involves a PSO-financed project aimed at solving the short-term problems, which occur in the experimental development and demonstrations of Danish fuel cell and stack technology. The second part of the project (EFP) represents a five-year plan aimed at establishing a long-term development path, leading to the reduction of the operating temperature of a fuel cell without increasing area specific resistance.

- **Finland** – a PEM module for microCHP (combined heat and power) is under construction (1.5 kW).

- **France** – Gaz de France and Electrcité de France are testing several units of small (1-5 kW) stationary fuel cells in five locations in France for residential applications and CHP.

- **Germany** – has been involved in demonstrating high temperature fuel cells (MCFC, SOFC) for stationary applications over the past decade. The national *ZIP program* includes projects specifically related to fuel cells, such as programs for the development and demonstration of fuel cells for residential applications (2-5 kW PEM). The *ZIP program* concentrates on further development and demonstration of six 250 kW MCFC block power plants and the 125 kW SOFC block power plant.

- **Italy** – from 1985 to 1997, Italy reports several demonstration activities for PAFCs in order to evaluate and validate the performance and durability of small on-site co-generation systems and to gain experience in their operation and maintenance (50 kW at Eniricerche in Milan and 200 kW at ACoSeR in Bologna). Additionally, a 1.3 MW demonstration plant for utility applications has been constructed by Ansaldo Ricerche, in cooperation with ENEA and AEM (the Municipal Energy Authority of Milan), and tested in Milan. The activities in this field were stopped in 1997, owing to the difficulties of this technology in reducing cost to the value required for the introduction into the market (1,000-1,500 €/kW). Italy has also undertaken the construction and demonstration of 100-500 kW systems for distributed power generation, with different fuels (natural gas, biomass gasification, etc.); and, the development of pre-commercial plants is planned in the next five years.

- **Netherlands** – fuel cell research activities include SOFC and PEM, including demonstrating local CHP generation and the virtual power plant concept, which is testing some 30 PEM systems in the field.

- **Norway** – has developed the *Utsira project* to demonstrate and test the viability of stationary fuel cell applications. Utsira is a small community on an island, isolated from the electricity grid and thus making it possible to demonstrate an autonomous energy system. The project consists of using a wind turbine to produce electricity. The excess electricity will be used for producing hydrogen by electrolysing water. The hydrogen is then stored, and will be used

as backup producing electricity from a hydrogen combustion engine, and an FC when there is no wind. The installation was officially opened in July 2004.

- **Portugal** – the *EDEN project* is an €8 million demonstration project directed at establishing the basis of a National Plan investigating the viability the production of energy using fuel cells. *EDEN* is operated cooperatively between the research laboratories and universities INETI, INEGI and IST and industrial companies CPPE, EFACEC and AUTOSIL.

- **Spain** – a Spanish/Italian consortium, with the participation of Ansaldo Ricerche, ENEA and ITAE in Italy and Spanish partners Iberdrola, Endesa and Babcock & Wilcox, constructed a 100 kW MCFC plant sited in San Agustín de Guadalix (near Madrid). IZAR Co has experience in operating a 250 kW MCFC since November 2002, which supplies electricity and heat to its motor factory. INTA and CIDAUT have demonstrated PEMs for residential applications. PEMs have also been demonstrated and integrated with a reversible heat pump and photovoltaic field for powering air-conditioning and electric installations in CARTIF Technological Centre.

- **Switzerland** – the Paul Scherrer Institute (PSI) established a strong collaboration with ETHZ to improve bipolar plates for PEMs. The result of this collaboration was the liquid-cooled 1 kW PEM PowerPac, which was first demonstrated at the Hannover Fair in 2002.

- **Sweden** – has been active in demonstration of PAFC units and was very active during the 1960s in developing AFCs for use in submarines. However, this latter development was not fulfilled when the former ASEA-company dropped out, but the development continued to some extent at the Royal Institute of Technology. During the early 1990s, the Lund Institute of Technology has achieved a number of developments in the area of SOFC use in combination with gas turbines.

- **Turkey** – through TUBITAK-MRC, a 500 kW MCFC demonstration plant is being operated in Turkey.

- **UK** – with support from the UK Department of Trade and Industry, Rolls Royce was the lead partner in the EU *MF-SOFC* and *CORE-SOFC* projects (see entry for Denmark). The Department of Trade and Industry has recently awarded a grant of £3.0 million to Rolls Royce to continue its development of pressurised SOFC systems for stationary power applications. The UK is also evaluating the long-term performance an IFC C25C 200 kW PAFC system at the Woking Borough Council's Leisure Centre. In addition, Intelligent Energy is presently demonstrating several small (1-5 kW) PEM fuel cell systems in a variety of stationary and remote power applications. Under the DTI's *Roadmap for Fuel Cells*, the UK plans to demonstrate by 2008 an integrated pressurised SOFC/gas turbine hybrid system of ~ 1 MW, with well-optimized distribution between SOFC and GT. Also, by 2010, the UK plans to demonstrate a series of at least four fuel cell systems in commercial and residential applications for stationary power.

Japan

Japan's Stationary Fuel Cell Demonstration Project operates 31 stationary fuel cells at various residential, heavy traffic, and seaside sites. It is perhaps the most comprehensive national demonstration program, which also evaluates the use of various fuel types (e.g., natural gas, LP Gas and kerosene). Japan's *Demonstration Project on Distributed Power Generation and Grid Connection* operates solar, wind and fuel cell (typically MCFC) simultaneously by using information

technology and technologies for minimising fluctuations. Last year, the Japanese government embarked on a major fuel cell demonstration project known as the *JHFC Project*, under which it operates stationary PEM systems in a number of domestic and office buildings.

Korea

A few PAFC stacks had been imported and tested for operation by several researchers until LG-Caltex successfully operated a domestically-manufacutered 50 kW system from 2000 to 2002. More recently, a 3 kW PEM system has been successfully tested by CETI in cooperation with KIER, LG Chemical Co, Kukdong Towngas Co, KOGAS Corp, and KEPRI. In 2004, Korea started a series of stationary fuel cell demonstrations which the 1-3 kW class PEM and a 250 kW MCFC system for distributed power. Domestically developed PEM systems by CETI, FCP and Daegu Towngas, were put into operation to decide the commercial product model most suitable to Korea and to solve the problem of grid connection. Three FCE 250 kW MCFC systems will be installed by 2005 in a steel mill and a sewage treatment facility. Coke oven gas from steel mills, LNG, and biogas from sewage treatment will be evaluated as fuel. POSCO in association with RIST, KIST, and Hyosung Heavy Industry will be in charge of operation. Korea is also developing a 100 kW MCFC with industrial participants, including KEPRI, Hyosung Heavy Industry and Samsung.

North America

The *Early Adopters* program is led by the Canadian government (Industry Canada) and seeks to work in partnership with industry stakeholders to foster the development and early adoption of hydrogen technologies. It will enable firms to showcase their technologies in working pilot-scale versions of a hydrogen economy and will help increase investor and consumer awareness of Canadian capabilities and the many benefits and uses of hydrogen-powered applications. The program is funded with C$50 million over five years. Other stationary applications include:

- **SOFC** – a Siemens Westinghouse Power Corporation demonstration of SOFC electrical generator prototype and development of balance-of-systems components for a SOFC CHP to generate up to 250 kW, enough for 50 homes.
- **PEM** – BCHydro/Ballard Airgen 1.2 kW utility backup power system.
- A Photovoltalic-Hydrolizer-PEM integrated demonstration system will provide back up power for the National Research Council Building in Vancouver; a SOFC demonstration system will provide additional back up power to the same building.

The US *Stationary Fuel Cells Program* aims to validate stationary fuel cells with a 30,000-hour durability, greater than 32 percent efficiency, and a price of $1,250/kW or less (for volume production). Reported funding for fuel cell stationary applications are concentrated on PEM, with a budget of US$7.5 million. Also, cooperative R&D programs, such as the *Solid-State Energy Conversion Alliance* (SECA), aim to reduce fuel cell technology costs and to increase durability and reliability. Additional cooperative, field evaluation programs, which include end-users such as utilities, will be used to continually focus the R&D.

The US is also developing the *Power Park concept*, which focuses on the steady production of hydrogen and use of a fuel cell to produce electricity. When excess hydrogen is available, it is stored for use when electricity demand is high and/or to refuel vehicles. The advantages of producing both hydrogen and electricity in Power Parks include: (1) it provides access to better natural gas rates because of higher volume than for a vehicle refuelling facility only; (2) it facilitates staged

implementation of refuelling components to better match the demand from vehicles; and, (3) it allows use of a larger reformer which will lower the per-unit capital costs of hydrogen production. The Power Park concept is amenable to distributed production of hydrogen from natural gas, and opens the possibility of incorporating wind and solar energy effectively. Analysis of the Power Park concept is ongoing and three State utilities (Detroit Edison Electric, Arizona Public Services and the Hawaiian Electric Company) are demonstrating this concept.

Chapter 2.
HYDROGEN PRODUCTION

Overview on hydrogen production

While advancements in fuel cell technology tend to grab the headlines, a critical hurdle blocking the road toward a viable "hydrogen economy" is the efficient, cost-effective and clean production of hydrogen. In terms of hydrogen production, there a several caveats to consider:

- It is essential to understand that hydrogen is not an energy source, but rather an energy carrier. And although hydrogen may be the most abundant element in the universe, pure hydrogen (H_2) – the fuel of choice for fuel cells – does not exist naturally and must be extracted from hydrogen-rich material like natural gas, coal and water. Therefore, in evaluating hydrogen production alternatives, the challenge is not about producing energy, but rather about using energy to produce hydrogen which will later be reconverted into energy.
- Although hydrogen is often touted as a clean energy resource, it is only as clean as the energy feedstock and technologies used to produce it. Currently, the most prevalent and least-expensive way to produce hydrogen is to derive it from natural gas through a process called "steam reformation." That process, however, generates CO_2 as a by-product. Hydrogen also can be derived from water through electrolysis, but if the electricity is generated from a coal-fired power plant, the "clean" hydrogen also carries with it the upstream emissions associated with coal production, transportation and use.
- Although it may be relatively simple to generate hydrogen by electrolysis, i.e. running an electrical current through water, the cost of producing the hydrogen also includes the upstream costs of generating the electricity. If the electricity is generated from renewable energy sources, the cost of hydrogen production includes the costs embodied in renewable power generation.

Researchers are developing a wide range of processes for producing hydrogen economically and in an environmentally-friendly way. Most methods of producing hydrogen involve electrolysis – or splitting water (H_2O) into its component parts of hydrogen (H_2) and oxygen (O). The most common of process is currently steam reforming of natural gas, which converts methane (and other hydrocarbons in natural gas) into hydrogen and carbon monoxide by reaction with steam over a nickel catalyst. Other methods include:

- High-temperature steam electrolysis uses heat (approximately 1000°C) to provide some of the energy needed to split water, making the process more energy efficient.
- Thermo-chemical water splitting uses chemicals and heat in multiple steps to split water into its component parts.
- Photo-electrochemical systems use semi-conducting materials (like photovoltaics) to split water using only sunlight.
- Photo-biological systems use micro-organisms to split water using sunlight.

- Biological systems use microbes to break down a variety of biomass feedstocks into hydrogen.
- Gasification using heat to break down biomass or coal into a gas from which pure hydrogen can be generated.

Electrolysis – An overview

Notably, electrolysis opens the door to producing hydrogen from any energy source capable of generating electricity, including fossil fuels, nuclear and renewable energies, such as solar, wind, or hydropower. But electrolysis requires substantial amounts of electricity, and is ultimately only as environmentally-friendly as the energy source used to generate the electricity. In terms of the ideal "hydrogen economy", it is anticipated that the electricity required for the electrolysis process would come from renewable sources – because the production of hydrogen fuel that increases demand for fossil fuels promises no greenhouse gas mitigation (under current scenarios and absent effective CO_2 capture and storage). Currently, electrolysis provides only a small percentage of the world's hydrogen, most of which is supplied to industrial applications requiring small volumes of high purity hydrogen. Finally, it is expected that it will be decades before improvements in renewable energy technologies would yield generate electricity at a price which would enable hydrogen to compete with conventional forms of energy.

Industrial electrolysis systems currently have hydrogen production capacities of up to 5 tons per hour and net system efficiencies up to 70-75%. Such systems operate with a net power consumption of around 40-45 kWh per kg of hydrogen produced. Current R&D efforts are aimed at improving net system efficiencies of commercial electrolysis toward 85%. The following science and technology challenges are examples of emerging key areas for on-going fundamental R&D efforts related to electrolysis: catalyst developments; electrode surface area optimization with nano-technology techniques; electronic charge carrier transport and surface reaction kinetics of doped metal oxides; fluid-dynamic optimisation; doped high-temperature ceramic membrane materials; surface modification of proton exchange membranes (polysulphone); steam electrolysis (yttrium ceramic); high-pressure electrolysis.

Hydrogen from Fossil Fuels

Hydrogen gas can be derived from hydrogen-rich fossil fuels through a variety of processes. Currently, the most prevalent and least-expensive way to produce hydrogen is to derive it from natural gas through a process called steam reformation. Hydrogen can also be "harvested" from coal, through gasification. Fossil fuels can indirectly be used to produce hydrogen when they are used to generate electricity used in the electrolysis of water. Since this practice includes emissions related to the fossil fuel consumption, hydrogen R&D programs involving electrolysis from fossil energy sources tend to include work on methods to reduce these emissions, such as carbon capture and storage. The current hydrogen world production rounds to some 40 million ton a year. Most of this hydrogen is produced from steam reforming of natural gas and used in refinery as a process gas, in chemical industry and in metal manufacturing.

Steam reformation

Steam reforming uses thermal energy to separate hydrogen from the carbon component of hydrogen-rich fuels by reacting them with steam on catalytic surfaces. Although steam reformation is a relatively efficient and inexpensive process, this depends upon the fluctuating price of natural gas (or other feedstock fuel). In terms of the environment, steam reformation generates CO_2 emissions, both as a by-product of the reformation process and during fossil fuel production and transportation (upstream) phases. As such, research typically focuses on how to make the process more efficient (i.e. gaining net energy in the production process) and utilising waste heat for other purposes (e.g. cogeneration). To the extent that steam reformation produces emissions of CO_2, researchers are also exploring methods of carbon-sequestration to prevent atmospheric emissions.

A number of IEA countries have undertaken research into the steam reformation of fossil fuels. Australia's initiatives include examining the potential for producing hydrogen for use in fuel cells for transportation and co-generation from coal-gas, natural gas and coal seam methane. Belgium has a €850,000 program investigating hydrogen generation from natural gas and alcohols. The German company Linde AG recently installed a decentralised natural gas steam reformer to produce hydrogen at the Munich airport refuelling station. The reformer fulfils the requirements due to the operation of the refuelling station including load changes. Korea has allocated Won8 billion to the production of hydrogen from natural gas. In the Netherlands, a long-running program has focused on using indigenous natural gas for conversion to hydrogen, using gas purification, reforming, catalytic partial oxidation techniques. The US has given significant attention to the use of natural gas resources as feedstock for the production of hydrogen. Elements of the US work include a US$4.2 million program for conventional and advanced reformation of natural gas. DOE's 2013 goal is to reduce the cost of hydrogen production from natural gas by 25%. The goal for distributed production of hydrogen from natural gas is US$1.50/kg (delivered, untaxed) at the pump (without carbon sequestration).

Gasification of coal

Gasification of coal may be the oldest method of producing hydrogen. This technique was the source of the "city gas" that was originally supplied to many cities in Europe and Australia before natural gas became available. This gas contains up to 60% hydrogen, but also large amounts of CO. To make it, the coal is typically heated to 900°C where it turns into a gaseous form; it is then mixed with steam and in the presence of a catalyst a mixture of H_2, CO and CO_2 is produced. In addition, sulphur and nitrogen compounds are released during the process, which like the CO and CO_2, must be handled in an environmentally-friendly way.

In order to take advantage of abundant coal resources, the US has a major (US$5 million) program aimed at the development of advanced and novel technologies to produce hydrogen from coal, including separation and purification focusing on hydrogen separation membranes, and other technologies including: integrated ceramics, water gas shift membrane reactors, defect free thin films, and inorganic membranes. By 2006, the US hopes to identify advanced hydrogen separation technology including membranes tolerant of trace contaminants.

Australia also has abundant coal resources and focuses on coal gasification as part of its *COAL 21 program*, which includes research on carbon sequestration as part of the national clean coal strategy. The objective is that Australia's vast coal reserves would remain a long-term, secure and cost-effective source of energy, but rather than burn the coal power plants would gasify that coal and capture and sequester the CO_2 in geological formations.

The German *COORETEC* (CO_2 Reduction Technologies) concept favours coal gasification with pre-combustion capture to introduce CO_2 capture into coal fired power plants. The same capture process is suited to produce hydrogen from coal in an environmentally-friendly way. This technical option is outlined in the recently drawn up national vision on hydrogen technologies. The first projects in this area are to be funded in the near future.

In Spain, ELCOGAS produces hydrogen at its industrial hydrogen production plant, based on the utilisation of coal in an integrated gasification combined cycle. France's IFP (Institut Francais du Petrole) has been active for many years in hydrogen production and is investigating different processes for producing hydrogen through the generation of synthesis gas from fossil fuels. The IFP is also developing new options for producing hydrogen with CO_2 sequestration. The Italian PNR Program is developing hydrogen production through a *Zero Emission Coal* (ZEC) project. The Polytechnic Institute of Milan is also conducting research into hydrogen production from fossil fuels with CO_2 sequestration and co-production of electricity. In Portugal, INETI is studying co-gasification in a fluidised bed for hydrogen production.

In Japan, there is a project aimed at capturing the considerable volume of hydrogen gas which can be obtained as a by-product steel production. R&D will focus on the purification process of fuel from coke oven gas to an acceptable level for fuel cell utilisation. METI, the Japan Research and Development Centre for Metals and Nippon Steel are working on the project with a 2003 budget allocation of ¥549 million. Japan also operates the *EAGLE* project which aims to develop an optimum coal gasifier for fuel cells and the establishment of gas clean-up system for purification of coal gas to the acceptable level for utilisation for MCFC and SOFC. The budget allocations for 2000-2003 total ¥4.6 billion.

US activities under the *Hydrogen from Fossil Fuels Program*, provide a good indication of key R&D work to improve the production of hydrogen from coal gasification:

- Advanced water-gas shift reactors using sulphur-tolerant catalysts to produce more hydrogen from synthesis gas at lower cost.
- Novel membranes for advanced, lower cost separations of hydrogen from carbon dioxide and other contaminants.
- Technology concepts that combine hydrogen separation and the water-gas shift reaction.
- Technologies that utilise fewer steps to separate carbon dioxide, hydrogen sulphide, and other impurities from hydrogen.
- Reforming for producing hydrogen from high hydrogen-content, coal-derived liquid fuels.

○ Other fossil fuel sources

- In **Spain**, INTA, CIDAUT, and CSIC are collaborating in the production of hydrogen from diesel fuel, designing the catalysts and the reformer and integrating it with a PEM. The University of Barcelona and Ansaldo Ricerche (Italy) worked together in developing a heterogeneous catalytic reactor for methanol partial oxidation.
- In **Turkey**, TUBITAK-MRC is studying hydrogen production from diesel fuel for PEM fuel cells.

- In **Canada**, hydrogen production from natural gas via a fluidised bed reactor with hydrogen purification via a selective membrane is under investigation. Also, a methanol micro-reformer which includes an integrated metal membrane purification unit is being developed.
- In **Portugal**, INETI is studying hydrogen production using steam reforming of natural gas, using biomass gasification at high temperatures for the steam reforming, followed by further water shift reaction. Catalysts are also used.

Hydrogen Production Pathways

The development of a wide-area hydrogen production infrastructure could take one or more pathways.

Distributed Production Pathway

A distributed production infrastructure could consist of natural gas or liquid fuel reformers, or electrolysers located at the point of use, i.e., refuelling stations and stationary power generation sites. This approach may be the most viable for introducing hydrogen as an energy carrier. It requires less capital investment for the smaller volume of hydrogen needed initially, and it does not require a substantial hydrogen transport and delivery infrastructure. However, carbon sequestration in distributed systems will be difficult and costly because of economies of scale. So, while centralised production benefits from economies of scale, distributed production may reduce hydrogen delivery costs. In the longer term, centralised production will be more cost effective in most cases, but distributed production will still play an important role.

Centralized Production Pathway

A second approach would be to produce hydrogen centrally using any one of a variety of feedstocks, both fossil and renewable. Coal and natural gas are possibly the least expensive feedstocks, but carbon sequestration is required to reduce or eliminate the high level of greenhouse gas emissions. Gasification or pyrolysis of biomass is a viable approach in many countries. Photo-electrochemical and photo-biological hydrogen production are embryonic technologies that have potential to produce hydrogen by splitting water with sunlight, but they can currently only produce small amounts of hydrogen at high cost. Water electrolysis is a viable approach where there is very inexpensive electricity. High-and ultra-high-temperature thermo-chemical hydrogen production that uses nuclear or solar heat sources may be viable with the development of appropriate water-splitting chemical process cycles and materials. Other feedstocks and technologies for hydrogen production that show promise may also be considered. Central production of hydrogen could potentially include a diversified feedstock base, but to be commercially viable it would require development of a distribution infrastructure for the produced hydrogen.

Hydrogen from renewable sources (using electrolysis)

The idea of a hydrogen economy based on renewable energy sources is continuously gaining importance, largely due to increasing concern regarding growth of energy demand, global warming and security of fuel supply. For these reasons, and in the long-term, renewable energy sources are expected to provide the energy to produce hydrogen. For this to happen, large-scale renewable energy production is an essential precondition for the credible deployment of a sustainable hydrogen economy. In the meantime, hydrogen technologies may help increase the penetration of renewables as back-up power for intermittent energy sources. And, hydrogen production may be used as an energy storage mechanism of any surplus electricity, performing peak-shaving and load-levelling energy services. Electrolysis technologies will clearly be an important element of the cost efficiency of using renewable energy to produce hydrogen. To this end, R&D in Japan for example has already yielded the development and demonstration of high efficiency PEM electrolysers.

Wind

A good example of R&D into the potential of renewable hydrogen production is the €1.7 million Utsira demonstration project sponsored by the Norwegian government. The project is evaluating the sustainability of using a wind turbine to generate electricity feeding an electrolyser for producing hydrogen, which in turn will be used in PEM fuel cells. In Sweden a hydrogen filling station went in operation in Malmö in September 2003. The hydrogen production is from electrolysis of water using electricity from wind power bought by contract from the grid. The hydrogen may ultimately be used directly to fuel hydrogen fuel cell vehicles at the station, but the first step is to mix the hydrogen with natural gas for use in buses in Malmö. The Australian government and the University of Tasmania constructed two large wind turbines at Mawson Base in Antarctica with the objective to supply the base’s annual electricity requirements and to produce sufficient hydrogen for use as transport fuel. The Greek Centre for Renewable Energy Sources (CRES) is focusing on hydrogen production from renewables. European partners are collaborating in the development of two test sites in Spain and Greece for the exploitation of wind energy for the self-sufficient production, storage and use of hydrogen. The plants are being erected on the Canary Islands and Lavrion, Attica respectively. Germany is planning a variety of off-shore wind parks in the Northern Sea taking into consideration hydrogen generation to avoid long-distance transport of electricity in at least some of the parks. In Portugal, characterisation and simulation studies are reported by the Portuguese National Institute of Engineering, Technology and Innovation. In Spain, the University of Las Palmas de Gran Canaria is coordinating the European project *RES2H2*, which evaluates self-sufficient energy systems driven by wind energy, capable of generating hydrogen, electricity and water.

Solar

In Australia, research is under way on solar electrolysis applications for both the public and private sectors. With respect to solar-based hydrogen production, Canada is developing photovoltaic-electrolyser-fuel cell technologies, including storage capabilities. In Spain, INTA has gained experience demonstrating solar hydrogen production with a 7.5 kW photovoltaic field and is currently investigating the combination of hydrogen PEM fuel cells with photovoltaic powering systems used in telecom applications. In Italy, ENEA laboratories have built and tested an integrated plant for the production of hydrogen from photovoltaic, along with its storage and utilisation in fuel cells. Austrian company, Fronius, is also developing hydrogen production systems from PV via electrolysis. Portugal is developing studies at INETI on the production of hydrogen through solar

PV via electrolysis. In Canada, the National Research Council in Vancouver is also demonstrating the combination of hydrogen PEM fuel cells with photovoltaic and electrolyser powering systems as a back up power for buildings.

High-temperature solar

Researchers are also demonstrating that highly concentrated sunlight can be used to generate the high temperatures needed to split water or methane into hydrogen and carbon. Concentrated solar energy can also be used to generate temperatures of several hundred to over 2,000 degrees at which thermochemical reaction cycles can be used to produce hydrogen. Such high-temperature, high-flux solar driven thermochemical processes offer a novel approach for the environmentally benign production of hydrogen. Very high reaction rates at these elevated temperatures enhance the production rates significantly and more than compensate for the intermittent nature of the solar resource. There are fives routes for solar hydrogen production using concentrated solar radiation as the energy source of high-temperature process heat. In the solar belt, these technologies are likely to be much less costly than PV and they use water as the source of hydrogen:

- Solar thermolysis.
- Thermochemical cycles.
- Fossil fuels solar cracking.
- Solar reforming.
- Solar gasification.

Current EU research programmes include:

- Solasys – an R&D project to (1) Demonstrate the process of steam reforming of methane with the aid of solar energy to produce hydrogen-rich synthesis gas as a gas turbine fuel. (2) Explore the possibility of solar reformer interface with fuel cells.
- Study of the behavior of biomass subjected to concentrated radiation (solar pyrogasification). Determination of the conditions enhancing the production of either oils or gases for electricity generation or chemical preparation.

In the US, two programs were reported: High Temperature Solar Splitting of Methane to Hydrogen and Carbon, and Rapid Solar-thermal Dissociation of Natural Gas in an Aerosol Flow Reactor.

The Italian PNR program is aimed at the long-term development of hydrogen production through thermal solar by a metal oxides/redox process and iodine-sulphur and UT-3 processes for the water splitting.

Hydro

In Switzerland, hydrogen production work focuses on high pressure electrolysis of water, deriving from the extensively available hydropower plants. Djevahirdjian S.A. manufactures (since 1914) rough synthetic crystals using H_2 and O_2 produced by high pressure electrolysis (1,700 m^3 H_2/day) and installed large, high pressure H_2 storage vessels (20,000 m^3).

Cross-cutting

A number of countries are conducting general efforts for improving electrolysis. Belgian researchers from SCK/CEN and VandenBorre Technologies have been working on pressurised electrolysers for more than 25 years. This company is also the manufacturer, together with their main owner Stuart Energy in Canada, of the electrolysers in Malmö and Stockholm. Canada is developing a compact water electrolyser consisting of 1 MW blocks, as part of $2 million demonstration program. Canada's "Solar Hydrogen" project is developing catalysts to lower the temperature at which hydrogen can be extracted from water. Korea's Won3.4 billion program is focused generally on improving the efficiencies of electrolysis using electricity from any source. The US is developing "advanced electrolysis" – low temperature electrolysis using alkaline and PEM technologies (electrochemical compression, improved efficiency, lower cost, integration of renewable resources), and "high temperature solid oxide electrolysis" under a $3.5 million program. By 2010, the US hopes to verify renewable integrated hydrogen production with water electrolysis at a hydrogen cost of US$2.85/kg.

Hydrogen from Biomass

Thermo-chemical processes can also be applied to bio-resources such as agricultural residues and wastes or biomass specifically grown as an energy crop to produce hydrogen through pyrolysis and gasification. This process generates a carbon-rich synthetic gas that can be reformed into hydrogen using thermal processing techniques similar to fossil fuels reformation.

Gasification technology has been under intensive development over the last two decades; a number of demonstration facilities have been tested and many units are in operation. Until recently, biomass gasification has been employed to produce electricity or heat – which has rarely justified the capital and operating costs. But the increasing demand for hydrogen is driving research and development of biomass gasification projects.

A number of countries have allocated R&D resources towards the production of hydrogen from biomass sources. Austria, which has been a leader in developing biofuels for transportation, has two demonstration plants and several pilot projects dedicated to gasification, conversion and purification of biomass for hydrogen production. Belgium is investigating the production of hydrogen for fuel cell use from organic residues, and its *GAZOPILE* program focuses on fuel cell feeding from wood gas generation. In Norway, a bio-hydrogen project has the objective to identify a process to gasify biomass and generate hydrogen with a level of purity sufficient for use with SOFCs. Portugal, through INETI, has been focussing on fluidised bed technology for biomass and waste high temperature steam gasification and pyrolysis for hydrogen production, aiming at building a 2 kW pilot power facility incorporating an SOFC prototype. The fuel cell technology is provided by Forschungszentrum Jülich, in Germany.

Spain has several R&D projects for producing hydrogen from waste biomass sources, including the development of a bioethanol-to-hydrogen conversion facility, by ICP-CSIC and Abengoa Company, using fermentation processes; several research centres are investigating the gasification of biomass to obtain a hydrogen rich gas. A €62,000 project in Greece is designed to test catalysts and reactors for reformation of ethanol and biogas for hydrogen. The Greek Company, Helbio, is planning to commercialise an ethanol fuel processor system for hydrogen production from biomass for remote, off-grid locations and in areas of inexpensive ethanol production such as Brazil, China and India.

The Netherlands has a number of hydrogen from biomass projects under its *Bio-hydrogen Platform*, which is a collaborative effort among eleven Dutch institutes and universities concentrating on pyrolysis and supercritical water gasification. The Energy Research Centre of the Netherlands (ECN) has carried out a project under financial support of the Dutch government to evaluate different pathways to produce renewable hydrogen from biomass. In 2001, France initiated a R&D programme to develop high purity synthesis gas from biomass gasification (joint program IFP&CEA, €2 million/year).

In the US, the plan for 2010 is to develop and demonstrate technology to supply purified hydrogen for PEMFC from biomass at US$2.60/kg at the plant gate (projected to a commercial scale 75,000 kg/day). The objective is to be competitive with gasoline by 2015. There is also a "*Hydrogen Production from Biomass program*" funded at US$1.2 million, which includes pyrolysis, gasification and fermentation.

The EU sponsored *CHRISGAS* consortium (22 partners) aims to develop a large scale biomass gasification process (with the existing gasification plant in Värnamo, Sweden, as a base) to produce a clean, rich-in-hydrogen gas which can be used for the production of vehicle fuel. This program will likely be funded with €9.5 million. Under the *EU CUTE* project, there are two sites with small-scale biogas reformers, located in Stuttgart (supplied by Mahler IGS) and Madrid (supplied by CarboTech). The latest small-scale reformer installed in Europe was recently added to the hydrogen refueling station at the Munich airport.

The IEA Hydrogen Implementing Agreement (Task 16) contributes information and results on hydrogen production processes from biomass – of particular interest are fuel gas specifications for fuel cells.

Hydrogen production from nuclear energy

Hydrogen production holds renewed promise for nuclear energy, as nuclear-based hydrogen production can provide an essentially carbon emissions-free source of hydrogen, significantly reduce dependence on fossil fuels, and open a new area of application for nuclear energy that may eventually exceed the use of nuclear power for electricity.

Three approaches are being investigated: The first is to use nuclear heat to assist with the energy needs required by steam reformation for producing hydrogen from fossil fuels (e.g., natural gas.). Secondly, several direct thermo-chemical processes are being developed for producing hydrogen from water. For economic production, high temperatures are required to ensure rapid throughput and high conversion efficiencies. A third way, of course, is to use nuclear power to supply electricity for electrolysis.

Production of hydrogen via high-temperature steam electrolysis has the potential for much higher overall efficiency than room-temperature electrolysis. In particular, high-temperature electrolytic water-splitting supported by nuclear process heat and electricity has the potential to produce hydrogen with an overall system efficiency near those of the hydrocarbon and the thermochemical processes, but without the corrosive conditions of thermochemical processes, the fossil fuel consumption and greenhouse gas emissions associated with hydrocarbon processes. Specifically, a high-temperature advanced nuclear reactor coupled with a high-efficiency high-temperature electrolyser could achieve a competitive thermal-to-hydrogen conversion efficiency of 45-55 percent. A research program is under way at the Idaho (US) National Engineering and Environmental

Laboratory to develop a conceptual design for large-scale nuclear production of hydrogen via planar solid oxide electrolysis technology. The design effort is addressing solid oxide cell materials and configuration, performance, durability, operating conditions, economics, and safety. Single and multiple cell experimental studies are being conducted. Interim results indicate that this technology performs close to theoretical predictions and remains a viable means for hydrogen production using nuclear energy.

Four countries reported working on projects to produce hydrogen from nuclear energy: The Japan Atomic Energy Research Institute is preparing to demonstrate the production of hydrogen by using the excess heat from its High-Temperature Engineering Test Reactor (HTTR) for steam reforming of natural gas, and later with an iodine-sulphur thermo-chemical process. France, through research institutes such as the CEA, CNRS and companies like EDF and Framatome, is carrying out an R&D program on massive hydrogen production with innovative high temperature processes. Within this program, the CEA cooperates with the US DOE under the *GEN IV* umbrella to develop a thermo-chemical (iodine-sulphur process) cycle to produce clean hydrogen gas from heat from nuclear plants. The US has a US$6.5 million nuclear energy program to convert hydrogen from high temperature heat nuclear sources (and solar) with a projected cost competitive with gasoline. The US hopes to develop by 2015, high-and ultra-high-temperature thermo-chemical/electrical processes to convert hydrogen with a projected cost competitive with gasoline. Korea's Ministry of Science and Technology is also investigating electrolysis from nuclear power.

Photo-electrochemical

Photo-electrochemical (PEC) processes can produce hydrogen in one step – splitting water by illuminating a water-immersed semiconductor with sunlight. There are two types of photo-electrochemical processes. The first uses soluble metal complexes as catalysts. When these complexes dissolve, they absorb solar energy and produce an electrical charge that drives the water splitting reaction. This process mimics photo-synthesis, however, currently there is minimal experience in this process.

The second method uses semi-conducting electrodes in a photochemical cell to convert light energy into chemical energy. The semiconductor surface serves two functions, to absorb solar energy and to act as an electrode. However, light-induced corrosion limits the useful life of the semiconductor.

The key challenges to advance PEC cell innovation toward the market concern the progress needed in material science and engineering. The development of highly efficient corrosion-resistant photoelectrode materials and their processing technologies are most important. Since no "ideal" photoelectrode material for water splitting (e.g., optimal band gap and position) exists commercially, new materials have to be engineered and synthesised. Combinatorial chemistry approaches offer options for the associated necessary material screening. In addition, fundamental research on doping for band gap shifting and surface chemistry modification is required, including studies on the associated effects on surface as well as bulk semiconducting properties. From a systems integration point of view and to optimise the techno-economic performance of PEC water splitting systems, current-matching between photoanode and cathode and ohmic resistance minimisation deserve considerable materials design and engineering attention.

Research into photo-electrochemical processes is limited. In Australia, a research team at the University of New South Wales School of Materials Science and Engineering in Sydney, with industry support, is investigating mechanisms for improving the efficiency of producing hydrogen directly from water. The separation process would be energized by sunlight using photo-sensitive materials. The project includes the development of titanium-based photo-sensitive catalysing electrodes. In Spain, ICP-CSIC is investigating the catalytic process of photo-electrochemical production of hydrogen.

The *Consortium for Artificial Photosynthesis* between several Swedish Universities focuses on basic R&D on artificial photosynthesis using the sunlight directly to produce hydrogen from water. And, the Swedish National Energy Agency has set a 2006 target to reform hydrogen and oxygen from water with sun energy through artificial photosynthesis.

The US is developing advanced renewable photolytic hydrogen generation technologies, with a 2015 goal to demonstrate an engineering-scale system that produces hydrogen at a plant-gate cost of US$10/kg projected to commercial scale. The US is also planning to demonstrate direct photo-electrochemical water splitting with a plant-gate hydrogen production cost of US$5/kg projected to commercial scale.

The IEA Hydrogen Implementing Agreement (Task 14) significantly advanced the fundamental and applied science in the area of photo-electrolysis of water. The work is oriented toward evaluating the system efficiency and device lifetime. From a scientific point of view, research was focusing on the development of semiconductor materials and structures, on photosensitive dyes, on integrated photovoltaics/electrolysis systems, and on novel single – as well as dual-bed reactor arrangements. The participants are undertaking research within the framework of two coordinated subtasks: (1) Improvement of light absorption of a variety of wide-bandgap semiconductor materials by dye-sensitisation and other techniques, and the development of catalytic and protective layers for PEC cells. (2) Maximisation of efficiency of multi-junction water splitting systems and the assessment of reactor system designs for the photoproduction of hydrogen.

Japan, Sweden, Switzerland and the United States have been the official member country participants of Task 14. The following research groups were active in Task 14 during 2003: The National Renewable Energy Laboratories (NREL) in Golden, the Hawaii Natural Energy Institute (HNEI) and the University of California (UCal) in Santa Barbara, all in the United States of America; The University of Uppsala in Sweden; The University of Geneva, the University of Bern and the Swiss Federal Institute of Technology (EPFL) in Lausanne, all three in Switzerland; And the Photoreaction Control Research Center (PCRC) of the Japanese National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, Japan.

Work under the IEA Implementing Agreement yielded a number of key accomplishments, including:

- World-first water-splitting catalyst powder operating in VIS light – Japan.
- Encouraging preliminary results from transition-metal-oxide (TiO_2), metaloxide (ZnO) and III-IV compound (Ga, GaIn)) doping using either N_2 or C – the Netherlands, Sweden, Switzerland, the USA.
- Progress with the preparation and characterisation of photoanode thin-.lms (WO_3, Fe_2O_3), including doping (Ti, Al) using ultrasonic spray-pyrolysis, sputtering or sol-gel – Australia, the Netherlands, Switzerland, the USA.

- Promising conceptual development of novel planar, multi-junction PEC water-splitting cells – the USA.
- Completion of deposition and characterisation equipment for ultrafast screening of new electrochemical materials (combinatorial chemistry) – the USA.
- Development of modeling capability of photo-oxidation based on quantum transition theory – the Netherlands.
- Production of 100 mm × 100 mm demonstrator PEC water-splitting tandem cells (WO_3/TiO_2; Fe_2O_3/TiO_2), with scale-up program toward 300 mm × 300 mm devices – Switzerland and the UK.

Biological and photolytic systems

Recently, increased attention has been focused on photolytic and biological means of hydrogen production. For example, solar thermal processes, photo-electrolysis, photo-catalytic and photo-biological processes. Biological production of hydrogen using micro-algal photo-synthesis is a process whereby hydrogen is derived from organic matter and water by micro-organisms such as algae and cyano-bacteria. The most common examples of organic feedstock include biomass crops, agricultural as well as animal wastes, and soils. The natural micro-algal hydrogen metabolism has to be genetically engineered in order to achieve significant, "natural overproduction" of hydrogen.

Many small-scale projects have successfully demonstrated the ability of these technologies to produce hydrogen. The R&D is still in its infancy and production costs remain significant. Nonetheless, the body of knowledge in this area of research is increasing rapidly. Key areas for on-going fundamental R&D efforts related to biological hydrogen production systems include, but is not limited to:

- Studies of genetic mechanisms and biochemical pathways of hydrogen metabolism.
- Hydrogen metabolism investigations of micro-algae in daylight and darkness.
- Maximisation of photosynthetic efficiencies.
- Improvement of oxygen tolerance of algae.
- Hydrogen fermentation processes.
- Recycling of algal cells after hydrogen evolution process.
- Development of bioreactor systems that operate under visible light.
- Artificial photosynthesis.

In response to the survey, Austria reported research on photo-biological work, focusing on anaerobic digestion of different substrates and purification systems. In Canada, a project to study hydrogen production through fermentation and to increase yields has started. Areas to be studied include: strain selection and culture conditions, improvement through genetic manipulation. French research agencies CEA and CNRS conduct research in photo-biological processes in cooperation with other

European programs, in particular Sweden's *Consortium for Artificial Photosynthesis*. The photo-biological part of that program is included in the consortium for artificial photosynthesis. Several German universities are conducting research on biological production of hydrogen, including the Technical University of Hamburg, which is investigating heterotrophic hydrogen production from bacteria with support by the *Renewable Primary Products programme*. In Italy, the University of Padova is leading research into innovative methods of hydrogen production from biological processes with a budget of €7.9 million. In The Netherlands, research has been performed within two projects *Biohydrogen* (funded by the EU) and *Hydrogen from Biomass* (national funding). In addition, work has been performed at Wageningen University using photoheterotrophic fermentation where hydrogen is produced from organic acids, predominantly acetate. The Portuguese research Institute INETI is carrying out studies related to biophotolysis using green algae and bacteria for hydrogen production. The US *photolytic program* focuses on both photo-biological and photo-electrochemical hydrogen production processes and is funded at US$2.8 million. In Japan, an *International Joint Research Grant Program* for the development of a molecular device for photo-hydrogen production has been initiated.

Seven research groups from Japan, France and Germany are working together with the aim to develop a biomolecular device to produce hydrogen gas from water by light energy. Researchers from national institutes, universities and private companies are developing a highly efficient anaerobic digestion system in tandem with a hydrogen fermentation process (*Development of High Efficiency Hydrogen-Methane Fermentation Processes using Organic Wastes*). R&D for monitoring and controlling microbial populations, which are involved in hydrogen metabolism, hydrolysis, and methane formation in the anaerobic digestion process, are being supported.

A new Nordic collaborative *Bio-Hydrogen* program has been initiated by nine partners coordinated by Sweden, under funding from the Nordic Energy Program. Partners from Finland, Iceland, Denmark, Estonia and Latvia may also participate in a new *BioHydrogen initiative* under the IEA Hydrogen Implementing Agreement.

The IEA Hydrogen Implementing Agreement's Task 15 deals specifically with "biophotolysis". The overall objective of Task 15 over the next five years is to advance the basic and early-stage applied science in this area. The work investigates microalgal hydrogen metabolism, both in the dark and in the light, as well as the mechanisms that would allow the photosynthetic processes and hydrogen evolution reactions to achieve their maximum possible efficiencies. In addition, subsidiary metabolic processes require investigation, such as the efficient accumulation of large amounts of carbohydrates, the regulation of the photosynthetic processes and the recycling of the algal cells after hydrogen evolution is completed. Complex underlying genetic mechanisms and biochemical pathways are involved in these physiological processes and require significant research efforts.

Present participants in Task 15 are Canada, Japan, Norway, Sweden, the Netherlands, UK, and the United States. Task 15 is divided into four Subtasks:

- Light-driven Hydrogen Production by Microalgae.
- Maximising Photosynthetic Efficiencies.
- Hydrogen Fermentations.
- Improve Photobioreactor Systems for Hydrogen Production.

Hydrogen production from Boron

Since about 64% of world boron reserves are found in Turkey, scientific studies are being conducted in Turkey to investigate the potential of boron as a hydrogen carrying material for use in fuel cells. Turkey is planning to upgrade the utilisation of this natural source, and will invite researchers, investors and international organisations to cooperate on hydrogen energy studies.

Snapshot: US DOE Funding on Hydrogen Production Fiscal Year 2004

$17.3 million: *Renewables – direct water splitting using solar energy; thermal processes using biomass; advanced electrolysis from wind power.*

$4 million: *Nuclear – using heat from either nuclear power or solar collectors; high temperature water splitting; high temperature chemical cycles.*

$5 million: *Coal – separation of pure hydrogen gas from synthesis gas (carbon monoxide and hydrogen); technologies also applicable to biomass feedstocks.*

$12.2 million: *Natural gas – small, distributed systems to begin making hydrogen available at local refuelling stations.*

CO_2 Capture and Storage

Overview

Carbon dioxide capture and storage (CCS) offer a new set of options for reducing greenhouse gas emissions.

Methods now used to separate (capture) CO_2 from other gases include solvent techniques and membrane separations. Both methods require energy input to recover CO_2. More efficient, lower-cost separation techniques would improve the feasibility of CO_2 capture.

Potential storage options include depleted oil and gas reservoirs, deep un-mineable coal beds, and deep porous formations containing salt water. Oil and gas reservoirs exist only where there is an underground structure that includes a seal that can retain gas and oil, and subsequently, CO_2 for long periods. Considerable experience developed in enhanced oil-recovery operations will be available to guide CO_2 storage projects. Coal bed storage relies on adsorption of the CO_2 on coal surfaces, while storage in deep formations containing salt water makes use of the CO_2's solubility in salt water.

The main actors in existing projects tend to be companies involved in fossil fuel extraction and combustion: oil and gas companies, coal producers, and some car manufacturers. These include, but are not limited to BP, Exxon-Mobil, Shell, EdF, Ford, Statoil, Chevron-Texaco, Total, RWE, Ford, and General Motors.

The countries involved in existing research efforts are those that follow a more technology oriented approach in their national climate policy, including the US, Canada, Japan, Norway, the Netherlands, Australia, plus a number of EU Member States and the EU itself, which is funding a number of ongoing projects.

Research activities in this field are sponsored by both companies and governments, and carried out by university departments, independent scientific institutions or industry research bodies. The following is a summary of IEA member government activities.

Australia

Australia has a number of research programmes on CCS and Zero Emissions Technologies (ZET). The government has recently set several priority initiatives, including:

- Decreasing CO_2 emissions as a national research priority.
- Funding of CRC for Greenhouse Gas Technologies (CO_2CRC).
- Development of a national roadmap for CCS.

The Cooperative Research Centre for Greenhouse Gas Technologies (CO_2CRC) researches the logistic, technical, financial and environmental issues of storing industrial carbon dioxide emissions in deep geological formations. The CRC also researches the capture and separation of carbon dioxide from industrial systems. Major support from industry, research parties and government organisations along with international collaborators are ensuring that CO_2CRC has a strong role to play in the mitigation of carbon dioxide emissions to the atmosphere.

The CO_2CRC R&D programme has four main components: storage, capture, regional demonstration, and international collaboration. Storing CO_2 involves technologies for assessing sites for CO_2 storage, understanding subsurface processes, stratigraphy, geomechanics and petrology, geochemistry, short and long-term reservoir modelling, CO_2 storage in coals, and risk assessment. The programme for capturing CO_2 involves characterising Australian emissions, enhanced solvent-based systems, innovative membrane systems, innovative pressure swing adsorption systems, hydrate formation & cryogenic distillation systems, capture of CO_2 in brines and minerals, metal activated conversion of CO_2, and economic modelling of capture & storage systems. The demonstration programme involves pilot and demonstration projects, regional development models to decrease CO_2 emissions, CO_2 strategies for emission hubs and a hydrogen economy. The international programme includes the participation in the Carbon Sequestration Leadership Forum and work with the Intergovernmental Panel on Climate Change (IPCC) and other international collaboration.

Additionally, Australia is engaged in the following efforts:

- The *GEODISC program* has established that the geological features of Australia ensure it is well placed for geological storage of carbon dioxide. CO_2CRC will build on these findings and plans to achieve a demonstration project within the term of CO_2CRC.
- The Cooperative Research Centre (CRC) for Clean Power from Lignite addresses the development of technologies to reduce Greenhouse Gas Emissions (GHG) from lignite-fired power stations while enhancing Australia's international competitiveness for low cost energy. The technologies under development relate to both current technology (pulverised coal-fired boiler) power stations and to high efficiency advanced cycles. *http://www.cleanpower.com.au/*

- The Commonwealth Scientific & Industrial Research Organisation (CSIRO) is engaged in a number of projects relating to CO_2 sequestration, including:

  1. CO_2 Sequestration into Coal Seams. This project is directed at developing fundamental physicochemical descriptions of the coal/ supercritical CO_2 interactions as well as the coal/rock/water/CO_2 interactions. It will provide quantitative data which will form the basis for deciding what the critical environmental issues are regarding CO_2 underground;

  2. *Research and Technology Roadmap to Address the Barriers to Carbon Dioxide Injection into Deep Coal Seams*. The Roadmap will identify areas where research, development or demonstration is required for the technology to be used in Australia as a means of generating low greenhouse gas emission power from Australia's bountiful coal reserves.

Belgium

As a part of the Belgian *Carbon Sequestration research program*, a study is being conducted on the potential of CO_2 storage in the "Kempen"-Flanders region. This initiative is receiving financial support from Flemish government of roughly €150,000. Another study is being conducted on the influence of super critical CO_2 on reservoir rocks (funding of €250,000).

Canada

There has been interest in the implementation of components of *Zero Emissions Technology* (CO_2 capture, storage and utilisation) for some time in Canada. As a signatory of the 1997 Kyoto Protocol, Canada has a high level of commitment to the reduction of greenhouse gas (GHG) emissions. Under the 2000 Climate Change Action Plan, CO_2 Capture and Storage has been identified as one of the measures that could contribute to a reduction in national GHG emissions. Several projects are currently underway which involve public and private sector partnerships, and international collaboration, with several of these projects being led by the private sector.

Some current Canadian initiatives in CO_2 capture and storage include:

- Technology development and cost reduction of CO_2 capture using oxy-fuel combustion and amine separation;
- CO_2 capture from hydrogen plants and other high purity sources;
- Gasification of coal for electricity production and to acquire pure CO_2 suitable for storage;
- Study of acid gas (CO_2 and H_2S) underground injection;
- Monitoring of CO_2 storage in enhanced oil recovery;
- Enhancement of methane recovery through monitoring of CO_2 injected into deep coal beds;
- Storage capacity assessments of Canadian sedimentary basins, coal seams and oil and gas reservoirs.

Recently, the Canadian *CO_2 Capture and Storage Technology Network* (CCCSTN) was established due to interest and initiatives underway for the implementation of CCS technologies and to coordinate activities undertaken by various groups and/or entities working on research, development and demonstration of national CO_2 capture and storage initiatives.

The CO_2 *Capture and Storage Incentive Program*, announced in March 2004, is intended to help develop a market for CCS in Canada. Incentive funding will be used to support projects that demonstrate CO_2-based enhanced resource recovery in small-scale commercial settings, and to help abate the costs of CO_2 capture and storage. Developed in consultation with industry and provinces in western Canada, this initiative complements provincial initiatives such as Alberta's *CO_2 Projects Royalty Credit Program*, and is designed to reduce duplication of effort for applicants in the Alberta program. The Western Canada Sedimentary Basin is believed to be the most promising location for such projects.

Canada's *Clean Coal Roadmap* provides an outlook to the future and identifies technology pathways needed to allow coal to be used as a competitive environmentally clean energy resource for the production of electricity and or hydrogen The roadmap is focused on identifying technologies and energy system pathways for power plant retrofits and mid term new construction; as well as technologies for the 2020 time frame where longer term development, infrastructure planning and implementation is required.

The *Weyburn Monitoring and Storage Project* is an international research project intended to establish the degree of security with which greenhouse gases, particularly carbon dioxide can be sequestered in geological formations during large scale, commercial, enhanced oil recovery operations. This will be accomplished through the scientific mapping of the movement of CO_2 in the reservoir, and technical prediction of the future long-term storage and migration characteristics of the CO_2. The field laboratory is the Weyburn CO_2 Miscible Flood Project, located in south-eastern Saskatchewan, Canada, near the US border with North Dakota. The ultimate deliverable is a credible assessment of the permanent contained of injected CO_2 as determined by long-term predictive simulations and formal risk analysis techniques. Results will help answer questions raised by regulatory bodies as to the security of large volume CO_2 sequestration/storage not only in the Williston Basin but also at other basins where CO_2 storage is contemplated. The project duration is for four years, under C$20.5 million from participants including Natural Resources Canada, Saskatchewan Energy and Mines, Government of Alberta, US Department of Energy, European Community, EnCana Corporation, Saskpower, Nexen Canada Limited, BP, Dakota Gasification Co, TransAlta Utilities, ENAA Japan, and TotalFinaElf.

○ Germany

In Germany, it is recognized that by 2010, large new power generation capacity needs to be constructed under the current political commitments to reduce greenhouse gases. The efficiency requirements of new power plants will be very high in order to reduce CO_2-emissions. Also, if CO_2 is to be reduced beyond what is possible by efficiency improvements, power plants with CO_2 capture will have to be installed. In parallel, storage options for captured CO_2 have to be developed.

In order to respond to these requirements, the Federal Ministry of Economics and Labour has initiated COORETEC – CO_2-Reduction-Technologies for fossil fuelled power plants. After summarising the requirements, COORETEC has evaluated existing and future power plant technologies leading to a number of recommendations for national R&D on promising technologies. The following technologies were evaluated in detail:

- Steam power plants with highest efficiencies and post combustion capture of CO_2.
- Steam power plants with oxyfuel combustion (the fuel is combusted with a mixture of CO_2 and pure O_2); CO_2 is captured from the flue gas.

- Natural gas combined cycle power plants with highest efficiencies (NGCC) and pre- and post-combustion capture of CO_2.
- NGCC with oxyfuel combustion (the fuel is combusted with a mixture of CO_2 and pure O_2); CO_2 is captured from the flue gas.
- Combined Cycles with coal gasification, pre-combustion capture of CO_2.
- Combined Cycles with coal gasification and oxyfuel combustion (the fuel is combusted with a mixture of CO_2 and pure O_2); CO_2 is captured from the flue gas.
- Hybrid power plants using high temperature fuel cells, and capture of CO_2 from cathode off-gas.
- Technologies for CO_2-capture, using captured CO_2 as a basis for chemical industry or for methanol production, CO_2-storage options.

Italy

In Italy, the main activities of the *CO_2 Capture Project* (CCP) include screening and assessment of existing and new technologies; capture (pre combustion, post combustion, oxy firing); monitoring and verification of geological storage; and comparative economics of capture options. Options for geological storage of CO_2 include deep aquifers; oil and gas fields (depleted reservoirs, EOR); mineral sequestration; and, process treatment: Calcium oxide – Calcium carbonate cycle.

Italy is also investigating options for power generation, based on new cycles and advanced technologies, including gas turbines, gasification of coal (and biomass), and high efficiency/ultra low-zero emissions combustion.

Japan

Japan has the longest running carbon capture and sequestration technologies research program. The focal point of their program is the Research Institute of Innovative Technology for the Earth (RITE). Established in 1990 as a non-profit organisation authorized by the Ministry of Economy, Trade and Industry, RITE focuses on the development of innovative environmental technologies and the broadening of the range of CO_2 sinks. With a budget of ¥9.9 billion, RITE has been conducting R&D and research investigations as well as providing information to the public regarding advanced technologies and research.

- *Project for Biological CO_2 Fixation and Utilisation*. The focus of this project is to develop technologies to fix CO_2 in the flue gas when generating power. In addition to fixation of the CO_2, the project aims to achieve more than 10 times higher efficiency than natural vegetation utilising photosynthetic microorganisms capable of fixing CO_2 at a higher rate and at extreme temperatures. Technologies will also be studied in order to achieve production of substances from the fixed CO_2 such as hydrocarbons, lipids as well as manure, feed, amino acid and polysaacharide. The project is led by a consortium of research organisations and corporations including the Research Center for Advanced Science and Technology, University of Tokyo, Shikoku National Industrial Research Institute, and 15 companies including Hitachi, Ltd, Mitsubishi Heavy Industries, Ltd, and Taisei Corporation.

- *Project for Chemical CO_2 Fixation and Utilisation*. This project aims to develop technologies that may continuously recover high-concentration carbon dioxide from stationary sources by large-scale membrane processes, as well as produce useful substances (including methanol) through hydro-generation of the recovered carbon dioxide. Efforts will focus primarily on developing a polymer membrane with excellent separation, permeation and durability performances necessary for CO_2 separation from emission gas. In addition, efforts are being made to develop high performance catalysts with high CO_2 conversion and selectivity toward methanol, as well as to develop a reaction process of high-energy efficiency. This project is led jointly by RITE and the Project Centre for CO_2 Fixation and Utilisation with joint research partners: National Institute of Materials and Chemical Research, National Institute for Resources and Environment, and Osaka National Research Institute.

- *Project for CO_2 Fixation in Desert Area Using Biological Function*. The purpose of this R&D effort is the development of new plants adaptable to the desert environment. Widespread desertification, which has decreased the stock of CO_2 absorbents in the environment, has become one of the main causes of global warming and one of the most critical of global environmental issues. Plant biotechnology and genetic engineering methods will be applied to develop plants capable of withstanding the harsh desert environment of strong sunlight and dry soil. This research aims at improving plant resistance to drought and light toxicity by ensuring highly efficient photosysthesis through improvement to the critical enzyme RuBisCO. The research also aims at improving the mechanism of toxic-oxygen scavenging. Determining the mechanisms of salt-exclusion and osmotic regulation is yet a further aim of this research.

- *Study of Environmental Assessment for CO_2 Ocean Sequestration for Mitigation of Climate Change* (SEA-COSMIC). Part of RITE's Ocean Sequestration program, this project aims to determine the behaviour of liquid CO_2-seawater injection. This project will conduct research on the technologies of CO_2 transportation to intermediate depths of the ocean as well as to develop models to assess the environmental impacts near the area of injection, including the impact of increased levels of CO_2 on marine organisms. In addition to research, the project will produce a supporting survey on the research trends concerning CO_2 ocean sequestration in Japan and abroad. This is a joint research project sponsored by the National Institute for Mechanical Technology, Hokkaido National Industrial Research Institute, and the Central Electric Research Institute with the cooperation of Massachusetts Institute of Technology (MIT) and the Norwegian Institute for Water Research (NIVA).

The Netherlands

The Netherlands Agency for Energy and the Environment (Novem) recently studied the technical and economic feasibility of enhanced coal-bed methane recovery (ECBM) in the Netherlands. The work included an investigation of the potential coal-bed methane (CBM) reserves underground as well as the related CO_2 storage potential in deep coal layers. The economic evaluation of ECBM recovery analysed the costs of capturing and transport CO_2 from major stationary sources, modelling the production of ECBM using CO_2 injection and investigate the costs of gas production. The costs of on-site hydrogen and power production (including on site CO_2 removal and injection) were also evaluated.

Norway

The Norwegian government has had a carbon dioxide tax scheme on energy use in place since 1991, which has been effective in encouraging companies like Statoil and Norsk Hydro to investigate the effectiveness of capturing carbon dioxide and subsequently injecting the carbon dioxide into oil wells or other geological formations. The *Saline Aquifer CO_2 Storage (SACS) project*, developed around the Statoil-operated Sleipner Field in the North Sea, is the first case of industrial scale CO_2 storage in the world. Carbon dioxide is being injected into the Utsira formation, a thick saltwater-bearing sandstone at a depth of approximately 1 kilometre below the sea bottom. SACS does careful monitoring of the behaviour of the CO_2 storage facility. SACS was formed by a consortium of energy companies, research institutes and the EU Commission with support from national authorities in Norway, Denmark, The Netherlands, France and the U.K. Project partners and funders include: Statoil, IEA GHG, EU Energy Program, BP Amoco, Norsk Hydro, Exxon-Mobil, Vattenfall, TotalFinaElf, the geological surveys of Denmark, France and the U.K., Sintef Petroleum Research, IFP (France), and NITG-TNO (The Netherlands). Statoil and IEA GHG provide international co-ordination and project facilitation.

More recently, the Norwegian Research Council launched the *Norwegian National Climate Technology Programme* (KLIMATEK) in 1997. The objective was to stimulate a cooperative effort between Norwegian industry, research institutions and government using government funding of US$18 million (i.e. 25% government cost share). Most of the 50 projects in KLIMATEK's portfolio to date involve offshore petroleum production, process industry, gas fired power production with CO_2 capture and CO_2 storage. Select projects include:

- *Kvaerner Oil & Gas and W.L. Gore & Associates GmbH Project*. This project developed a gas-liquid membrane contactor utilising a novel membrane absorption process that aims to remove CO_2 from flue gas using amine absorption. Unlike conventional capture process technology, the Kvaerner process is both small and compact, enabling the technology to be utilised offshore. The exhaust gas flows through small Teflon membrane fibres, which are surrounded by the absorption liquid. CO_2 passes through the membrane and is carried away by the liquid. The huge membrane surface area results in a highly efficient absorption process, thereby reducing the size and weight of process equipment used significantly. The contactor has been demonstrated in a pilot plant at Statoil's gas processing plant in Kårstø on the west coast of Norway.

- *Zero Emission Gas Power (ZEG) Project*. This project addresses the problem of energy efficient co-production of electricity and hydrogen from natural gas with integrated CO_2-capture. The basic concept of the ZEG-process is to combine solid oxide fuel cells (SOFCs) and a hydrogen production process utilising the waste heat from the SOFC. Taking advantage of the fact that the fuel and air-streams can be kept separated in a SOFC-system and a novel reforming process featuring integrated CO_2-removal, it is possible to achieve high overall efficiencies and still capture the CO_2. Applications of the ZEG-process range from medium sized, 10 MW, "gas-stations" producing electricity for the local community and supplying FCVs with hydrogen, to large scale power plants in the 100 MW range. The ZEG-process bears resemblance to a process initiated by Los Alamos and now being developed through the Zero Emission Coal Alliance (ZECA) in the US.

- *CO_2 Storage Research Project.* This project recognises that storing CO_2 in geological structures is an attractive option outside Norway, both because of possibilities to improve oil production and existing large saline structures (aquifers) ideally suited for CO_2 storage. SINTEF Petroleum

Research and University of Bergen have both been awarded long term research contracts to improve understanding of fundamental mechanisms and critical issues of CO_2 storage in geological reservoirs. Sintef Petroleum Research is focusing on the development of an experimentally verified mathematical model of all processes involved in CO_2 injection and transformation of hydrate and removal/release of natural gas in reservoirs. University of Bergen is concentrating on aquifers and specifically fundamental geochemistry and hydrate mechanisms in relation to long-term safe storage.

- *Ship Transportation of CO_2 Project*. The aim of this project is to assess technical solutions and costs for different transport cases between capture sites (power plants and high CO_2-concentration process plants) and point of storage or use of CO_2 (aquifers and CO_2-EOR) in the Northern Europe/Norwegian Sea Basin.

- *Coordination Polymers as CO_2 Absorbents*. This is a long-term (2002-2006) basic research project conducted at the University of Oslo. In this project new and novel adsorbent materials (coordination polymers) will be studied that can selectively and reversibly adsorb/desorb carbon dioxide from ambient to 300°C.

United Kingdom

The UK Department of Trade and Industry (DTI) maintains several programmes that develop technologies and processes for power generation focused on improving environmental performance. Part of this work includes a review of technologies for capture, transport and storage of CO_2, and to establish technology maturity and where further effort is needed. Projects include:

- Gas-Zero Emissions Plant (ZEP). Alstom Power's Gas-ZEP project explores methods to capture the CO_2 as it is produced in a natural gas-fired power plant without substantial reductions in plant efficiencies.

- Development of Advanced Reservoir Characterisation and Simulation Tools for Improved Coalbed Methane Recovery. Led by Imperial College of Science Technology and Medicine, the main objective of this project is to develop technology and tools to more accurately assess the potential for improved methane recovery and CO_2 sequestration by investigating the basic scientific phenomena of CO_2 coal injection and retention. The researchers' primary objective is to achieve a more comprehensive understanding of the fundamental mechanisms of water and CO_2-CH_4 adsorption/desorption, diffusion/counter diffusion, and 2-phase flow under simulated reservoir conditions (stress, pore pressure, and temperature). The results of these studies will then be applied to design of a CO_2-ICBM recovery and CO_2 sequestration simulator for the European industry.

- High Pressure Interaction of Coal with CO_2: Implications for CO_2 Disposal and for Methane Displacement from Coal Seams. The project, led by the University of Strathclyde, aims to provide fundamental information about CO_2/coal interactions at high pressure in order to optimise methane displacement and CO_2 disposal. The project will investigate how much CO_2 can be stored in coal at different pressures and how difficult it is to diffuse through coals of different rank, while determining the amount of coal irreversibly absorbed. A range of experimental techniques will be used including high-pressure differential scanning calorimetry, volumetric adsorption, high-pressure gravimetric analysis, high-pressure small angle neutron scattering and temperature programmed desorption/mass spectrometry.

United States

The US carbon sequestration R&D work is comprised of a three-pronged strategy: (1) A coal R&D effort aimed at advanced gasification, coal-capable turbines and fuel cells, membrane technology, and carbon capture and sequestration; (2) the *Clean Coal Power Initiative* (CCPI) which has hosted a series of competitions conducted over a 10-year period to encourage demonstration of new coal-based power generating technologies; and, (3) the *FutureGen* project, which combines the most capable technologies emerging from the coal R&D program and the CCPI into a new type of power plant integrated with hydrogen production and carbon sequestration.

The US also manages the *Carbon Sequestration Leadership Forum* (CSLF), an international initiative that focuses on development of improved cost-effective technologies for the separation and capture of carbon dioxide, its transport and long-term safe storage. The objective of the CSLF is to make these technologies broadly available internationally; and to identify and address key issues. This includes promoting the appropriate technical, political, and regulatory environments for the development of such technology. Participating countries are Australia, Brazil, Canada, China, Colombia, France, Germany, India, Italy, Japan, Mexico, Norway, Russian Federation, South Africa, United Kingdom, United States, and the European Commission.

Currently, the US DOE is directly funding to more than 70 research projects across the United States and internationally: including 15 projects on the pre- or post-combustion capture and removal of CO_2; 17 projects on sequestration in all its forms – terrestrial, geologic, and some oceanic; 14 projects for measuring, monitoring and verifying sequestered carbon; 9 projects exploring breakthrough concepts; 3 projects to manage the non-carbon greenhouse gases; and 16 basic research projects within the U.S. National Energy Technology Laboratory. Select projects include:

- Advanced Oxyfuel Boilers and Process Heaters for Cost Effective CO_2 Capture and Sequestration. This project is to develop a novel oxy-fuel boiler to reduce the complexity of CO_2 capture.
- CO_2 Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream. This project aims to develop a process that captures CO_2 by combining it with water at low temperature and high pressure, thus forming CO_2/water hydrates, ice-like macromolecular structures of CO_2 and water. Laboratory experiments seek to determine the level of CO_2 removal achievable, measure energy requirements, and assess any negative effects attributable to hydrogen sulphide and methane gases.
- A Collaborative Project to Develop Technology for Capture and Storage of CO_2 from Large Combustion Sources. This project aims at proving the feasibility of advanced CO_2 separation and capture technologies. The team will develop an economic model to compare different approaches and will also develop guidelines for safe CO_2 storage in underground formations.
- Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents. This project aims to develop a CO_2 separation technology that uses a regenerable, sodium-based sorbent to capture CO_2 from flue gas. Thermodynamic analysis and preliminary laboratory tests indicate that the technology is viable. Process data will be collected to assess the technical and economic feasibility of various process configurations. This retrofit process is amenable to all conventional steam-generating power plants.
- CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2. This project aims to develop a high temperature CO_2-selective membrane to enhance

the water-gas-shift reaction efficiency, while recovering CO_2 for sequestration. The improved membrane is ideally suited to integrated gasification combined cycle power generation systems.

- CO_2 Separation Using a Thermally Optimised Membrane. This project aims to manufacture a high-temperature polymer membrane with better separation capabilities than current polymer membranes. The project focuses on the separation of CO_2, methane, and nitrogen gases in the range of 100 to 400°C.
- Geologic Sequestration of CO_2 in Deep, Unmineable Coalbeds. This project uses existing recovery technology to evaluate the viability of storing CO_2 in deep unminable coal seams in the San Juan Basin in northwest New Mexico and southwestern Colorado. The project will verify and validate gas storage mechanisms in coal seams, and to develop a screening model to assess CO_2 sequestration potential.
- Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams. This project aims to demonstrate the use of "slant-hole" drilling to degasify unmineable coal seams. Upon drainage of 50-60% of the CBM, CO_2 will be injected into some of the slant-hole wells to enhance CBM production.
- GEO-SEQ. This project investigates safe and cost-effective methods for geologic sequestration of CO_2. Targeted tasks address the following: (1) siting, selection, and longevity of optimal sequestration sites; (2) lowering the cost of geologic storage; and (3) identification and demonstration of cost-effective and innovative monitoring technologies to track migration of CO_2.
- Feasibility of Large-Scale CO_2 Ocean Sequestration. This project, operated by the Monterey Bay Aquarium Research Institute will use a Remotely Operated Vehicle (ROV) to deploy small quantities of liquid CO_2 in the deep ocean. Below about 10,000 feet the density of liquid CO_2 exceeds that of seawater, and the liquid CO_2 is quickly converted into a solid hydrate by reacting with the surrounding water. Using a Raman spectrometer, scientists will assess the impact that the CO_2 hydrate material has on the ocean floor and ecosystem.
- Sequestration of CO_2 in a Depleted Oil Reservoir. This project will investigate down-hole injection of CO_2 into depleted oil reservoirs in New Mexico. It will conduct a comprehensive suite of computer simulations, laboratory tests, field measurements, and monitoring efforts to understand the geomechanical, geochemical, and hydrogeologic processes involved. It will also use the observations to calibrate, modify, and validate the modelling and simulation tools.

European Commission

The European Commission's Research Directorate General supports zero emissions technologies for fossil fuels through a number of collaborative projects as listed below.

- CO_2STORE. This project investigates four new potential cases for CO_2 reservoirs primarily on land. It will continue reservoir simulations and study geochemical reactions to develop final-fate prediction models. This will be supported by new seismic observations. At the same time, gravimetrics is introduced as a new method better suited on land. This proposal is currently being negotiated and builds directly on the Thermie/5FP SACS2 project results, which involved monitoring and modelling the injection of CO_2 into the Utsira Sand aquifer, at Sleipner gas field, offshore Norway.

- European Potential for Geological Storage of CO_2 from Fossil Fuel Combustion (GESTCO). The principal objective is to provide a major contribution to atmospheric CO_2 reductions that will ensure a stable, affordable and environmentally acceptable supply of energy for all of Europe. In order to meet that objective, GESTCO is currently evaluating the CO_2 subsurface storage potential in four principal geological storage types that are known to exist in several regions throughout Europe, including: onshore/offshore saline aquifers with or without lateral seal; low enthalpy geothermal reservoirs; deep methane-bearing coalbeds and abandoned coal and salt mines; and exhausted or near exhausted hydrocarbon structures. Through various case studies of these geological types in different countries GESTCO will: produce detailed geological data for each area; evaluate the significance of all possibilities for alternative uses of the subsurface; evaluate the impact of any leak that may occur; define the location of potential storage areas relative to large point sources (power plants and major industrial sources) of CO_2; conduct reservoir simulations of each potential storage area; make an economic evaluation of the storage potential in each area, and conduct economic comparison of CO_2 free electricity production cost from conventional and renewable energy sources. This information will be utilized to create realistic scenarios that can help determine the cost of CO_2 avoided and/or the increase in cost of electricity generation. A dedicated decision support system can then be developed so that users can evaluate site-specific source/storage options and cost estimates. The main participants include: the geological surveys of Denmark, Great Britain, The Netherlands, France, Belgium, Norway, Germany and Greece, which work jointly within the EuroGeoSurveys Association. Private sector participation includes Ecofys (NL), Vito Engineering (B), Greek National Power Corporation, French Geothermal Company, and the National Oil Company of Denmark.

- CO_2NET. CO_2NET is the European technology-networking programme for CO_2 sequestration into geological storage. CO_2NET is working to establish and build a European Thematic Network of organisations and individuals to facilitate co-operation and, European-funded CO_2 projects. The Thematic Network will enhance awareness of European activities and fast-track the developing technologies to meet emissions reduction demands. CO_2NET's initial partners include the EC, IEA-GHG, Technology Initiatives, Ltd., the Portuguese National Institute of Engineering, Technology and Innovation, BP, and the British Geological Survey. The Geological Survey of Denmark and Greenland, also a founding member, manages the project.

- CO_2NET2. This will be the continuation of the CO_2NET accompanying measure. CO_2 Thematic Network will facilitate the development of CO_2 capture and storage as a safe, technically feasible, socially acceptable mitigation option. The foundations of the European CO_2 Thematic Network have been laid over the past 10 months by the CO_2NET initiative supported and funded by the EC. Within 10 months, 29 organisations in 9 European countries and the EU funded CO_2 projects have committed to support the Thematic Network to accelerate the enabling technologies towards CO_2 emissions reduction. Membership is expected to exceed 40 organisations in 2002.

- NASCENT. The NASCENT project is a European Commission project that commenced in February 2001 and run for 3 years. It is a study of CO_2 accumulations as analogues for geological storage and sequestration of anthropogenic CO_2 emissions. The project focuses on the porosity and permeability of host formations, the integrity of caprock, ground stability, and quality of ground water in overlying aquifers. The project coordinators are the British Geological Survey and partners include: Bundesanstalt für Geowissenschaften und Rohstoffe

(Germany); Bureau de Recherches Géologiques et Minières (France); Institute of Geology and Mineral Exploration, (Greece); Magyar Állami Földtani Intézet (Hungary); The Netherlands Institute of Applied Science (The Netherlands); Rheinisch-Westfälische Technische Hochschule, Aachen University of Technology (Germany) and Università "La Sapienza" di Roma (Italy). Also collaborating in the project are: BP; IEA Greenhouse Gas R&D Programme and Statoil.

- AZEP. The 3-year US$9 M EC-sponsored Advanced Zero Emission Power Plant (AZEP) project was initiated in 2001 to further develop and test key components such as a membrane reactor and heat exchanger and system integration for a 75 kW unit. A commercial scale demo plant is envisaged in 2007. Norsk-Hydro in co-operation with Alstom is developing a novel concept, which is based on a membrane combustor with integrated oxygen separation. It is envisaged that CO_2 capture can be achieved with significantly lower efficiency penalty than present concepts and that current gas turbine technology can be used hence facilitating retrofit applications.

- GRACE. This project sets out a 2-year programme that aims to develop technologies that will reduce the cost of capture and separation of carbon dioxide. In addition to existing technologies, the project will research and develop new technologies to feasible working models.

- RECEPOL. In this project the feasibility of greenhouse gas emission reduction by CO_2 storage in subsurface coal seams is studied. Locally produced CO_2 or flue gas from a power plant is injected in the coal at a selected test site in the Silesian Coal Basin (Poland), while CH_4 is produced simultaneously. The CH_4 can be used as fuel for clean energy generation, without net CO_2 emissions. Research is mandatory in this new and complex field of technology to design an optimum development plan for the site. This research involves laboratory work, model simulations, and investigation of time-lapse monitoring. Existing wells at the test site and a newly drilled well will be used for the test, and the injected gas is monitored in time. Together with an evaluation and field up scaling of the results the project will be concluded with a socio-economical and implemented in a Decision Support System.

- HyPOGEN will explore the limits of using hydrogen as a means of de-carbonising fossil fuels and therefore its potential to bridge to a future hydrogen economy. The aim of the project will be to develop and operate a pilot demonstration plant and prove the feasibility, safety and economics, of carbon capture and sequestration.

Other International Efforts

The US-managed *Carbon Sequestration Leadership Forum* (CSLF) is an international initiative that is focused on development of cost-effective technologies for the separation and capture of carbon dioxide, its transport and long-term safe storage. The objective of the CSLF is to make these technologies broadly available internationally; and to identify and address key issues relating to carbon capture and storage. This could include promoting the appropriate technical, political, and regulatory environments for the development of such technology. An agreement was signed by 15 countries: Australia, Brazil, Canada, China, Colombia, France, Germany, India, Italy, Japan, Mexico, Norway, Russian Federation, South Africa, United Kingdom, United States, and the European Commission.

The International Energy Agency *Greenhouse Gas Programme* (IEA GHG) is the leading international collaborative programme on technologies for reducing GHG emissions from fossil fuels. IEA GHG

conducts technical and engineering evaluations of technology options as well as identifying targets for development and demonstration and then facilitating the progress of such work. It disseminates the knowledge gained so as to enable decision on mitigation technology to be taken with best available information. IEA GHG was established in 1991 and has since conducted almost 90 separate investigations of technologies. The results form the basis for much of the current understanding and literature on the potential for CO_2 capture and storage. The IEA GHG is established under the terms of an Implementing Agreement from the IEA. There are currently 16 countries plus the European Commission that support the IEA GHG, along with 8 major industrial companies as sponsors. IEA GHG supports a number of collaborative efforts with industry and governments listed in this section.

The *CO_2 Capture Project* (CCP), formed in 2000, is an international effort funded by 9 of the world's leading energy companies in partnership with governments, industry, NGO's and other stakeholders. The project seeks to develop new technologies to reduce the cost of capturing and sequestering CO_2. The CCP accomplishes this objective by: performing bench top R&D (engineering studies, computer modelling, laboratory experiments) to prove the feasibility of advanced CO_2 separation and capture technologies, specifically tagging post-combustion methods, pre-combustion decarbonisation, and oxyfuel; developing guidelines for maximising safe geologic storage, for measuring and verifying stored volumes, and for assessing storage risks; developing an economic model to establish lifecycle CO_2 separation, capture and sequestration costs for current and best technologies actively transferring and making available the new technologies to industry via publications, presentations, conferences, an internet website, patent licenses and commercial services. The CCP is leveraging international commitments totalling about $28 million from the IEA GHG, EU, US DOE, and Norway's Klimatek Programme. Members of the CO_2 Capture Project are: British Petroleum, ChevronTexaco, Eni, Norsk Hydro, PanCanadian, EnCana, the Royal Dutch Shell Group of Companies, Statoil and Suncor Energy.

The *Saline Aquifer CO_2 Storage (SACS) project*, developed around the Statoil-operated Sleipner Field in the North Sea, is the first case of industrial scale CO_2 storage in the world. CO_2 is being injected into the Utsira formation, a thick saltwater-bearing sandstone at a depth of approximately 1 kilometre below the sea bottom. SACS does careful monitor the behaviour of the CO_2 storage facility. In addition to demonstrating feasibility of CO_2 storage in the Sleipner field, the project will also produce a "best practice" manual for CO_2 disposal. To date, approximately one million tonnes of CO_2 are stored in the formation. The SACS project investigates the Utsira formation and surrounding strata utilising repeated three-dimensional (3-D) seismic reflection surveys. The CO_2 "bubble" around the Sleipner CO_2 injection well in the Utsira formation was large enough and in such concentrations by September 1999 (3 years after initial injection) to be monitored by a 4D "time lapse" seismic survey. Before the project commenced, it was debated among geophysicists whether CO_2 could be monitored by standard seismic surveys. Expectations changed after the first geological analysis, reservoir simulations and seismic modelling done by the SACS project partners in spring 1999. A major shift in the budget was then made, reducing the volume of geoscience work and moving forward the second seismic survey to the summer 1999. Geochemical work has been hampered by scarcity of sample material. A core from Utsira sand and pore water has been used in initial short and long-term laboratory experiments and the data is still being processed. SACS was formed by a consortium of energy companies, research institutes and the EU Commission with support from national authorities in Norway, Denmark, The Netherlands, France and the U.K. Project partners and funders include: Statoil, IEA GHG EU Energie Programme, BP Amoco, Norsk Hydro, Exxon-Mobil, Vattenfall, TotalFinaElf, the geological surveys of Denmark, France and the U.K., Sintef Petroleum Research, IFP (France), and NITG-TNO (The Netherlands). Statoil and IEA GHG provide international co-ordination and project facilitation.

Chapter 3. HYDROGEN STORAGE, TRANSPORTATION AND DISTRIBUTION

Overview of hydrogen storage

Hydrogen is an extremely difficult gas to store, which will limit its use until convenient and cost effective storage technologies can be developed and commercialised. One gram of hydrogen gas, for instance, occupies about 11 litres of space at atmospheric pressure. So for convenience of use, it must be pressurised to several hundred atmospheres and stored in a pressure vessel. In liquid form, hydrogen can only be stored under cryogenic temperatures.

The present state-of-the-art in hydrogen storage is 350-bar and 700-bar compressed tanks, and cryogenic liquid hydrogen tanks. Tanks have been certified worldwide according to ISO 11439 (Europe), NGV-2 (U.S.), and Reijikijun Betten (Iceland) standards, and approved by TUV (Germany) and KHK (Japan). They have been demonstrated in several prototype fuel cell vehicles and are commercially available at low production volumes. All-composite, 700-bar tanks have been developed and have demonstrated a 2.35 safety factor (burst pressure) as required by the *European Integrated Hydrogen Project* specifications. Liquid hydrogen tanks have also been demonstrated and used in prototype vehicles. A few solid state storage materials, such as sodium borohydride and other chemical and metal hydride systems have been demonstrated in a concept vehicle.

Research is currently focusing on a variety of traditional and non-traditional gaseous, liquid and solid storage options which should enable hydrogen to be stored and used commercially and safely. The performance target for on-board hydrogen storage in fuel cell vehicles has not yet achieved and a major effort is required to overcome this key technology bottleneck. Most of the R&D efforts are conducted by private companies and imply proprietary information issues.

The IEA Hydrogen Implementing Agreement (Task 17) is oriented toward the development of new reversible hydrogen storage solid media with increased gravimetric and volumetric capacity, along with the development of fundamental understandings of those materials. The main application of interest is on-board vehicular hydrogen storage, although stationary storage is also in the Task's R&D planning. The vehicular storage work assumes a PEM fuel cell or internal combustion engine as the power plant, thus setting the temperature available from its waste heat. For efficiency, that heat must be tapped for the required enthalpy for hydrogen liberation from the storage media. The stationary storage work is oriented toward low cost and the handling/purification of impure hydrogen destined for fuel cell use.

Task 17 consists of a series of R&D projects led by project leaders from participating countries. Most involve international collaborations among participating individuals and institutions. The projects can be divided into three categories, by media: Hydride (H), Carbon (C) and combined Hydride/Carbon (HC). The HC projects include a few R&D topics that are neither hydride-nor carbon-based, strictly speaking. Since its founding in 2001, Task 17 has constituted the largest international R&D consortium ever established for solid state hydrogen storage materials.

Compressed gas

Hydrogen can be compressed and stored in high-pressure tanks. The compression process, however, requires significant input energy – and the low energy volume density of hydrogen gas does not compare well with the energy content of liquid fuels like gasoline stored in similar sized containers. Though this means of storage is feasible for stationary applications which are not usually bound by size and weight restrictions for storage containers, it is less practical for transportation because the conventional pressurised metal tanks are heavy and expensive. The research in this field – mostly, industrial research – has developed new, fiber-composite, high-pressure vessels, which might in principle compete with other storage technologies.

Canada's current R&D program includes efforts to develop safe, efficient and cost effective hydrogen storage materials, components and systems. As part of its *Fuel Cell Commercialisation* program, Canadian IMW Industries is developing a high-pressure hydrogen compressor and dispenser system for small- and large-scale hydrogen fuelling stations. This hydrogen compressor system is intended to ensure full fill at 350 and 700 bar. The improved design and energy recovery techniques will lower operating and maintenance costs and reduce the amount of energy required to compress hydrogen. Also, Canadian Dynetek has developed 350-bar stationary cylinders and on-board storage cylinders for fuel cell vehicles.

In France, Air Liquide and CEA are developing new high-pressure hydrogen tanks for on board storage, using innovative materials (polymer material for liners, all "plastic tanks"), rated at 350 to 700 bar. Spain also reported hydrogen storage work focusing on the development of commercial compressed gas cylinders. Swiss efforts also include work on the high pressure storage of gaseous hydrogen in composite cylinders, especially in light weight CNG-4 tanks. The EU STORHY project is one of the most advanced projects on compressed and liquid hydrogen storage development.

Japan's industry has also developed and demonstrated compressed hydrogen storage technologies to support the country's HFC commercialization program. Japan's fuel cell vehicle performance targets for 2020 include development of an on-board 5 kg hydrogen storage container to enable a 500 km driving range.

Hydrogen storage activities within the DOE Office of Hydrogen, Fuel Cells and Infrastructure Technologies also focus on the research and development of on-board vehicular hydrogen storage systems that allow a driving range of 300 miles or more. US Quantum Technologies has developed a 700 bar vessel for on board storage

Cryogenic storage

The cryogenic storage is achieved by refrigerating hydrogen to – 253 degrees Celsius, transforming the gas to liquid and enabling bulk amounts of hydrogen to be shipped commercially by truck and rail. However, the liquefaction procedure uses a significant percentage of hydrogen's energy content – as much as 30% – and requires special materials and handling. The storage tanks are insulated, to preserve temperature, and reinforced to store the liquid hydrogen under pressure. The cost of the energy required for the liquefaction process, combined with the cost of tanks required to sustain the storage pressure and temperature results in a very expensive storage option. A key issues of liquid hydrogen storage is maintaining the low temperatures that liquid hydrogen requires. Research in the field of liquid hydrogen storage centres on both the development of composite tank materials to achieve lighter, stronger tanks and improved methods for liquefying hydrogen. A method in the early stages of development uses vacuum to evaporate liquid hydrogen, with the temperature falling down to 259 degrees Celsius. This creates more dense storage possibilities for hydrogen.

Japan's programs have historically focused on hydrogen storage elements, including a number of liquefaction and transportation technologies for liquid hydrogen. Austrian activities include successful demonstration of Magna Steyr's liquid tank system used in a number of major vehicle demonstrations. Switzerland is developing liquid organic hydrogen storage systems, so-called quasi-liquid systems, i.e. suspensions of microscopic metal hydrides in organic solvents. Canada reports research on magnetic liquefaction and the development of an active magnetic refrigerator prototype. In Germany, car manufacturer BMW and gas engineering company Linde are actively developing lighter storage systems for liquid hydrogen. Recently, a world patent was granted to Linde on reducing boil-off losses as an important result of the public funded CEP project.

Hydrides

Metal hydrides are specific combinations of metallic alloys that act similar to a sponge soaking up water. Metal hydrides posses the unique ability to absorb hydrogen and release it later, either at room temperature or through heating of the tank. The total amount of hydrogen absorbed is generally 1% -2% of the total weight of the tank, although some metal hydrides are capable of storing 5%-7% of their own weight. Although the percentage of gas absorbed to volume of the metal remains relatively low, hydrides offer an intriguing storage solution because they can safely deliver extremely pure hydrogen at a constant pressure.

A number of countries reported research on hydrogen storage in metal hydrides, including the Nordic Energy Research program which features a project on new metal hydrides and another on advanced hydrogen storage materials. Norway has conducted basic research on hydride storage and is working on six development projects. Norway also participates in the EU's *STOREHY* hydrogen storage program. Finland participates in the Nordic program, and is pursuing the development of new metal hydrides for hydrogen storage, including results from the Finnish company Hydrocell which develops alkaline fuel cells and metal hydride storage systems.

Austrian company Treibacher is developing MeH materials for solid storage systems. In Italy, the PNR program is also developing innovative materials for storage. Switzerland is working on a large number of metals and alloys which have been screened and tested with respect to optimal hydrogen storage capacity, but also with respect to technically feasible charge/discharge characteristics. Research in the UK has produced some promising results for light metal hydrides. Canadian research focuses on metal hydrides (including alanates), thermal hydrogen compression on hydrides, and absorption. In Portugal, INETI is working on nano-structured materials for hydrogen storage in order to establish criteria for assessing the effect on the stability of the M-H bond and its modification in the course of hydrogenation and to assess the reversible capacity for hydrogen storage of alloys. In Spain, Inasmet foundation also reports hydrogen storage work in the area of metallic hydrides, including synthesis by conventional techniques and through self propagation high temperature synthesis liquid or metallic hydrides. Spain also participates in the EU's *STORHY* hydrogen storage program. Japan reports a number of R&D efforts in the area of metal hydride storage systems with strong participation of industry.

Turkey reports investigating applications of Boron compounds. To this end, Turkey is establishing the Boron Institute, which will investigate new application areas for boron and its compounds.

US DOE is investigating two types of hydrides for solid-state hydrogen storage: complex metal hydrides and chemical hydrides. DOE's research on complex metal hydrides is focused on increasing the storage capacity of alanates, extending the durability and cycle lifetime, and improving uptake

and release reproducibility. Thermodynamic and kinetic studies of the alanate system now underway will serve as the basis for systematically exploring other complex hydride systems. Engineering studies are also underway to facilitate the design of optimized packaging and interface systems for on-board transportation applications.

DOE's research on chemical hydrides is focused on developing low-cost energy-efficient regeneration systems. Significant technical issues remain regarding the regeneration of the spent material and whether regeneration can be accomplished on-board. In addition, life cycle cost analysis is needed to assess the costs of regeneration.

○ *Nanotube (Carbon Material) Storage*

Carbon nanotubes are microscopic tubes of carbon, two nanometers (billionths of a metre) across, that store hydrogen in microscopic pores on the tubes and within the tube structures. The advantage of carbon nanotubes is – in principle – the amount of hydrogen they are able to store. The US Department of Energy has stated that storage materials need to have a storage capacity of 6.5% of their own body weight to be practical for transportation uses. Preliminary experiments with carbon nanotubes showed very high storage performance from 4% up to 65% of their own weight in hydrogen. This high performance however has not been confirmed by further experiments. Active R&D is still in progress to understand the real potential of such materials for hydrogen storage. The focus is on improved, low-cost manufacturing techniques. It is however still questionable whether and when nanotubes may become a viable or commercial mechanism for storing hydrogen.

In Australia, the University of Queensland in Brisbane is investigating hydrogen storage in carbon nanotubes. Griffith University, also in Brisbane, is investigating storage in nano-materials including degradation mechanisms in $LaNi_5$ and hydrogen absorption by nano-structured carbons. Griffith University is also conducting direct measurements in real time of the quantity of hydrogen stored in these novel materials. In Belgium, SYNATEC is working on the synthesis of multi-wall and single-wall carbon nanotubes. Germany recently funded a joint research project on the detailed investigation and optimization of hydrogen storage in carbon nanostructures for stationary and mobile applications with €2 million. The Greek "Demokritos" (NCSR) Institute of Materials Science works on nanostructure hydrogen storage technologies, and under the Government's *Renewable Energy Sources and Energy Saving program*, research is being conducted into storage of hydrogen in nano-structures. Research in Portugal focuses on the development of nano-structures of carbon from biomass, and INETI is studying its production using pyrolysis and evaluating its capacity for hydrogen storage. Spain also hopes to develop large scale production of carbon nanotubes by catalytic decomposition of hydrocarbon materials over nanostructural metallic surfaces; and hydrogen adsorption capacity of carbon molecular sieves, in some cases drugged with alkaline elements, will also be studied. Canadian research focuses on carbon nanomaterials, production and characterisation of nanofibers, and determinations of hydrogen storage capacities. US DOE work also has a focus on developing carbon nanotubes as an on-board storage method for vehicles.

○ *Chemically Stored Hydrogen*

As the most abundant element in the universe, hydrogen is often found in numerous chemical compounds. Some of these compounds can be used as a hydrogen storage method. The hydrogen is combined in a chemical reaction that creates a stable compound containing the hydrogen. A second reaction occurs that releases the hydrogen, which is collected and utilised by a fuel cell.

The exact reaction employed varies from storage compound to storage compound. Some examples of various techniques include ammonia cracking, partial oxidation and methanol cracking. These methods eliminate the need for a storage unit for the hydrogen produced, where the hydrogen is produced on demand. The US reported work on the chemical storage of hydrogen. The University of Graz in Austria is investigating the sponge iron process using synthesis gases from different industrial processes for the reduction step. The total efficiency of the process, the cycle-ability of the iron material, and the conversion efficiencies of available industrial waste gases containing synthesis gases are the major contents of the projects.

Across the board

Korea conducts a range of basic research of hydrogen storage and utilisation. MOST is engaged in compressed gas and cryogenic liquid hydrogen storage for industrial applications. R&D also includes storage in metal alloys and carbon nanomaterials. The target for 2012 is the development of high pressure gas-storage cylinder (700 bar) and advanced cryogenic technology to store liquefied hydrogen.

In the UK, at least 22 UK universities have been involved in researching issues associated with hydrogen and a large number of these have ongoing research into chemical and physical hydrogen storage. In addition, companies located in the UK such as BP, Shell and BOC have been active in assessing safety issues related to the storage and distribution of hydrogen. The Fuel Cell Vision Paper described elements of a R&D, focusing on hydrogen storage and hydrogen grid. The UK DTI routemap for fuel cells laid out a number of actions pertaining to developing commercial hydrogen storage containers, including a viable hydrogen storage system suitable for passenger cars by 2005.

The EU "STORHY" program aims to develop the next generation of compressed and liquefied hydrogen storage and metal hydrides. The EU consortium includes about 40 partners including car industry players. The program is support with a €10 million budget.

The US plans a substantial increase in DOE funding for 2005 to initiate the Grand Storage Challenge, which will focus on compressed/liquid H_2Gas, metal hydrides (including alanates), chemical hydrides, carbon structures, new materials and testing/analysis. US storage R&D objectives are to develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications. Funding levels have increased since FY 2003 for storage R&D. The level in 2003 was US$10.8 million, 2004 was US$29.4 million and the 2005 request is US$30 million. A key activity in 2005 will be to initiate three "Centres of Excellence" to demonstrate hydrogen storage activities.

Transportation and distribution of hydrogen

Overview

Whether produced from fossil or non-fossil sources, the widespread use of hydrogen will require a new and extensive infrastructure to produce, distribute, store and dispense it as a vehicular fuel or for stationary applications, such as electric generation. Depending on the source from which hydrogen is produced and the form in which it is delivered, many alternative infrastructures can be envisioned. Tradeoffs in scale economies between process and distribution technologies, and such issues as operating cost, safety, and materials can also favour alternative forms of infrastructure.

In terms of transportation and distribution, there appears to be general consensus on two broad approaches:

- Small-scale local hydrogen production, based on either electrolysis or gas reformation, thus utilising existing electricity or gas distribution infrastructure.
- Large-scale dedicated hydrogen production infrastructure, including, pipelines and or road transport.

The first option has a number of attractions from the viewpoint of minimising distribution costs, although it could make it more difficult to achieve the economies of scale associated with large-scale hydrogen production and to capture and store CO_2 when hydrogen is produced out of fossil fuels. It also requires augmentation of both gas and electricity production and distribution infrastructure. This investment could be in addition to that required to integrate renewable energy into the electricity grid system, depending upon the renewable energy sources relative to hydrogen demand centres.

Current hydrogen delivery infrastructure exists only for limited industrial hydrogen markets for chemical and refining industries in Europe and in the United States. Those limited systems lack the scope or scale needed to deliver hydrogen outside of these few industrial areas to potential large-volume end-user applications. Therefore, it is likely that significant capital investment in dedicated hydrogen delivery infrastructure will be required before a hydrogen economy can be realised. Alternative approaches include using the existing natural gas delivery infrastructure. These systems, however, would require significant modification for use in the delivery and distribution of hydrogen. For example, hydrogen has physical properties that may cause embrittlement of some high-strength steel piping materials and components (e.g. compressors and valves) currently used for natural gas.

The evaluation of options also includes the use of an alternative liquid fuel as consideration for a hydrogen carrier, such as hydrogen-rich liquid fuels (e.g., coal-derived methanol and Fischer-Tropsch liquids). Analysis is also needed to evaluate the trade-offs that exist between the use of existing liquid fuel and natural gas infrastructure to deliver hydrogen-rich fuels and the massive capital investments required for implementing a system with central hydrogen plants, associated pipelines, and distribution centres in a dedicated hydrogen infrastructure. It may be the case that these hydrogen-rich fuels can be economically reformed at end-use locations, instead of central locations. The cost of small-scale, on-site reforming and the associated benefits should be evaluated against the large capital costs of a dedicated hydrogen infrastructure.

In any case, an efficient transportation and distribution of hydrogen from the production site to the end-user is needed for the wide-spread use of fuel cells envisioned by the hydrogen economy. Key R&D areas for improving hydrogen transportation and distribution infrastructure include:

- high pressure gaseous storage and supporting technologies;
- hydrogen pipelines based on natural gas pipeline industry;
- hydrogen compressors;
- compressed gas tube trailers;
- cryogenic liquid storage, insulation and supporting technologies;
- cryogenic tankers for bulk-transport of liquid hydrogen;
- absorbent/adsorbent hydrogen storage solid media and supporting technologies;
- hydrogen bulk storage systems and bulk dispatch terminals;
- fuelling stations and supporting technologies.

○ *Synthesis of IEA government activities*

Although many countries mentioned transportation and distribution as among their overall hydrogen and fuel cell development programs, few delineated specific work elements or budget allocations.

In Japan, transportation and distribution work can be found throughout the *JHFC* programs. *WE-NET* incorporated hydrogen transportation and storage technologies with the implementation of demonstration programs and the construction of refuelling infrastructure. Japan's ¥3.5 million demonstration project on *Distributed Power Generation and Grid Connection* is designed to evaluate a variety of distributed energy systems, including solar, wind and fuel cell. Japan also funds a program for the *Development for Safe Utilization and Hydrogen Infrastructure*, which includes a network of production plants utilising a variety of hydrogen reformation techniques, transportation by liquid hydrogen or high-pressure pipeline, storage and refuelling. As of December 2003, JHFC stations have fueled 2,527 kg of hydrogen for 1,315 FCV's. Three additional stations have been constructed in FY 2004, as well as a liquid hydrogen production facility, which has been constructed and will supply liquid hydrogen to Ariake station in FY 2004. In addition, two hydrogen stations will be installed by the end of January 2005 to support fuel cell buses in Aichi.

In Belgium, Air Liquide Industries has built a hydrogen grid covering Belgium, the North of France and the South of the Netherlands. It connects chemical industries and oil refineries. A similar hydrogen grid exists in Germany. Canada is planning to construct a "H_2 Highwayv for the 2010 Winter Olympics, including 8-10 hydrogen refuelling stations. The US *Hydrogen Delivery program* is oriented toward defining a cost-effective, energy-efficient, and safe hydrogen fuel delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power. This focused effort on hydrogen delivery is a new program element and includes objectives to, by 2010, develop technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use for vehicles or stationary power units to less than US$1.30/gge of hydrogen.

The EU also sponsors two transportation and distribution oriented programs:

- NATURALHY – project aims to define the technical and socio-economic conditions to inject hydrogen in natural gas using the existing infrastructure in a transition to the H_2 economy. 48 partners are involved including major EU gas utilities with a budget of €11 million.
- HYWAYS – program aims to build a European Hydrogen Roadmap in order to investigate and model the impact of different hydrogen pathways and associated technologies into a wide range of sectors. This program includes 40 partners and a budget of €4 million.

Quick facts – hydrogen pipelines

Network of 720 km in USA and 1,500 km in Europe.

Pipe steel, operate at a pressure of 10-20 bar, 25-30 cm in diameter.

Energy loss for transportation is about 4%.

The oldest (> 50 years) network is in the Ruhr area of Germany.

Transmission costs are about 50% higher for hydrogen as compared to natural gas.

Chapter 4.
HYDROGEN SAFETY, CODES & STANDARDS

Overview on hydrogen safety, codes and standards

Safe practices in the production, storage, distribution, and use of hydrogen are essential components of a hydrogen economy. Hydrogen is a potentially dangerous substance because its low volumetric energy density requires very high pressure for gaseous storage and cryogenic temperature for liquid storage, for both mobile and stationary applications. However, its risk level as a fuel is similar to that of fuels such as natural gas and propane. Like all gaseous fuels, however, hydrogen can be handled and used safely with proper safety precautions, and strict adherence to rules, regulations and standards established through experience and research.

Codes and standards are also required for designing, building, testing, and ultimately commercialising and trading hydrogen technology components and systems. The need of international codes and standards for hydrogen technologies is of global interest and has repeatedly been identified as a major institutional barrier to developing and deploying a hydrogen economy. This need is not confined to any one country – harmonising international standards is a global challenge.

National governments such as the US, Canada, and Japan are leading the way by developing concrete programs to facilitate and accelerate development, and to support research and certification investigations that will be necessary to build a basis for codes and standards. Much of the work in this area aims to significantly accelerate the identification of current gaps, and to evaluate the adequacy of existing and newly-developed standards.

One important forum for international harmonisation is the UNECE-WP29. It has made two proposals for UNECE regulation on hydrogen vehicles that are now under consideration for potential implementation as European Directives. However, a full consensus has not yet been reached at the international level. Non-European players, namely the US and Japan are seen to favour a direct development of global technical regulations.

Summary of the IEA Governments' activities

○ Australia

Australia's national hydrogen study recognises that development and adoption of appropriate international codes and standards for various hydrogen technologies, including those relating to fuel cells, is of primary importance. Through bodies such as the IEA, the Asia Pacific Economic Co-operation (APEC) and the International Partnership for the Hydrogen Economy (IPHE), Australia plays an active role in the process to ensure that codes and standards applicable to hydrogen are compatible with the country's participation in a future hydrogen economy.

Europe

The EU *HySafe network* focuses on issues to improve understanding of hydrogen safety and to support the safe and efficient introduction and commercialisation of hydrogen as an energy carrier. The program includes 25 European partners and is supported with a €7 million budget. The project is coordinated by the research centre of Karlsruhe, Germany and includes the development of a common approach to risk assessment and codes & standards.

Many European countries are also independently developing codes and standards. Austria reports demonstrations of "pre standards" for establishing fuel cell CHP systems providing heat loads up to 70 kW, along with several standards for hydrogen in the field of welding. In the Denmark, the Risoe National Laboratory program activities include non-technical issues such as normalisation, safety, codes and standards. In Germany, a joint project led by the German Technical and Scientific Association for Gas and Water (DVGW) has worked out safety regulations, codes and standards for the use of hydrogen in stationary fuel cells. The German company LBST has coordinated the EC funded projects *EIHP* and *EIHP2*. In Norway, the Government established a Hydrogen Commission to define targets to develop hydrogen as an energy carrier and to develop projects with emphasis on safety codes and standards. Norway is also an active participant in the EU projects. Norwegian companies participate in EU projects such as *HyNet, Hysafe*, *CUTE*, and *Safety and Quality*, where they are responsible for regulation and safety. Spain has defined safety as a priority for realising the potential of hydrogen and fuel cells, with a major program initiative to design and demonstrate safe and competitive use of residual hydrogen for combined cycle optimisation. Spain is also adopting rules to the ISO TC 197 related to hydrogen technologies and a National Committee has been formed to steer this process. Also in Spain, INTA takes part in several European projects within the scope of safety, codes and standards, such as *FEBUSS*, and participates in the *European Integrated Hydrogen Project*, which provides inputs for regulatory activities – at European and global level – to harmonise procedures for approval of hydrogen-fuelled vehicles and refuelling infrastructure. In the United Kingdom, the DTI *Fuel Cell Vision Paper* sets out scenarios for the fuel cell industry development in UK. A major objective is to develop a clear policy framework – including developing international codes and standards in cooperation with the international community – in order to provide long-term continuity and a context in which industry can flourish. Companies such as BP, Shell and BOC have been active in assessing safety issues related to the storage and distribution of hydrogen.

Japan

Japan has undertaken significant efforts in this area, in particular to establish codes, standards and regulations to bring fuel cells to the market. The *New Hydrogen Project* (NHP) extends the work initiated in *WE-NET* and ties together a number of METI's ongoing and new programs.. The project focuses on R&D on testing methodologies and data acquisition for PEM vehicles, hydrogen refuelling stations and stationary PEM systems. The goal is to promote international standardisation and establish performance and safety testing methods for public use. The 2003 allocation for this activity is ¥3.86 billion. The NHP is oriented toward creating regulations suitable for market introduction of hydrogen-fuelled fuel cells by 2005. This involves liaison between government (Cabinet Secretariat, Cabinet Office, National Police Agency, Fire and Disaster Management Agency, Ministry of Environment, METI and MLIT) and industry. The objective is to review 28 regulations and 6 laws: High Pressure Gas Safety Law; Electricity Utilities Industry Law; Traffic Law; Road Tracking Vehicle Law; Fire Law; and Building Standard Law.

Japan's *Millennium Project* also promotes the establishment of codes and standards for the popularization of PEM systems, including fuel quality, safety and reliability, and regulations for soft infrastructure. The R&D focus is on testing methodologies and data acquisition for PEM vehicles and stationary PEM systems. The goal is to promote review of existing regulations, international harmonisation of fuel standards, and performance and safety testing methods. Under Phase Two of the *WE-NET* program, safety tests were already conducted on FC vehicles, namely on fuel tanks and refuelling.

North America

Canada is a leader in the development and implementation of international codes and standards for hydrogen safety. The *Early Adopters* program is led by Canada Industry and seeks to work in partnership with industry stakeholders to foster the development and early adoption of hydrogen technologies, codes and standards. Also, the Canadian *Transportation Fuel Cell Alliance* will develop standards, training and testing procedures as related to fuel cell and hydrogen technologies. Much of the work aims to contribute to the global effort to develop coordinated hydrogen and fuel cell standards that are required for hydrogen to be a safe and cost-effective energy carrier. Canada also reports general support for safety, codes and standards implementation including participation in ISO TC 197 and the development of a Canadian Hydrogen Installation Code for hydrogen fuelling stations – a study to establish appropriate clearance distances for hydrogen fuelling stations, the "Virtual Fuelling Station", and hydrogen sensor technology.

The US addresses codes and standards issues to identify current gaps in the standards development process and to evaluate the adequacy of existing and newly-developed standards. The objectives in this area include facilitating the creation and adoption of model building codes and equipment standards for hydrogen systems in commercial, residential, and transportation applications; providing technical resources to harmonize the development of international standards among the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the Global Regulation on Pollution and Energy (GRPE) Program. The US government is addressing domestic and international codes and standard issues in the recognition that affordable hydrogen and fuel cell technologies must be developed and domestic and international codes and standards must be established simultaneously to enable the timely commercialisation and safe use of hydrogen. Funding allocations for codes and standards work totalled US$4 million in 2003, US$6 million in 2004 and US$15 million has been requested for 2005.

Currently thirteen US and two international standards development organisations are developing and publishing the majority of the voluntary domestic codes and standards. These organisations typically work with the public and private sectors to craft standards. In the US, the American National Standards Institute (ANSI) coordinates standards development, provides guidance on consensus building, recommends that no more than one standard is developed per technology, and acts as a central point of contact for the harmonisation of international standards.

US objectives in the area of safety include:

- Complete the drafting of hydrogen building codes for the National Fire Protection Association's (NFPA's) hearing cycle.
- By 2005, facilitate the adoption of the International Code Council (ICC) codes in three key regions: Northeast, Mid-Atlantic, and Midwest.
- By 2006, support and facilitate the completion and adoption of the ISO standards for hydrogen refuelling and storage.

- By 2008, support and facilitate the completion and adoption of the revised NFPA 55 standard for hydrogen storage with data from Technology Validation subprogram activities and the experimental project for underground bulk storage of hydrogen.
- By 2010, support and facilitate U.S. adoption of a Global Technical Regulation for hydrogen fuel cell vehicles under the United Nations Economic Commission for Europe World Forum for Harmonization of Vehicle Regulations Working Party on Pollution and Energy under the GRPE program (ECE-WP29/GRPE).

The US government is currently drafting a comprehensive safety plan to be completed in collaboration with industry. The plan will initiate the research necessary to fill safety information gaps and allow integration of safety procedures into all DOE project funding procurements. The US DOE will also publish a *Handbook of Best Management Practices for Safety* by 2010. The Handbook will be a "living" document that will provide guidance for ensuring safety in future hydrogen endeavours. The US Safety subprogram focuses on the following activities:

- Determining the physical and chemical properties of hydrogen and whether they are accurately reflected in hydrogen's safety classification.
- Conducting safety reviews of current and future projects, including practices and procedures.
- Developing and publishing a comprehensive database on safety, including component reliability, sensors, and hydrogen releases.

Chapter 5.
POLICY STUDIES & TARGETS

Overview of IEA government policy studies

Virtually all of the countries reported activities in policy studies. In some cases, the policy work is broad in nature, setting out general goals and objectives for hydrogen and fuel cell work over the long run. For example, Australia's *National Hydrogen Study*, completed in September 2003, investigates the role of hydrogen in the energy future mix, particularly in the context of the country's abundant fossil fuel and renewable energy resources. It also examines opportunities to produce hydrogen for domestic and export markets. Since the completion of the study, the Australian government has released an energy White Paper in which it acknowledged the long-term importance of hydrogen as an energy carrier and the need for Australia to be involved in the development and adoption of appropriate international codes and standards. In relation to the provision of funding for hydrogen initiatives, R&D under way in Australia is largely associated with broader government programs. These support, for example, Australia's participation in bodies such as the International Partnership for the Hydrogen Economy as well as the country's participation in established forums such as the IEA and APEC.

Canada's *Fuel Cell Commercialisation Roadmap* was an industry-led planning process supported by the government with the objective to accelerate full-scale commercialisation of fuel cell technologies by Canadian fuel cell companies. The *Roadmap* was developed through the participation of many leaders in industry, government and academia. It represents a critical step in identifying the commercialisation challenges and in selecting the strategies and actions that will allow Canadian stakeholders to successfully meet these challenges. A work plan has been drafted to begin implementing the report's recommendations. With the completion of the *Roadmap*, hydrogen will now be examined in the broader context. A number of additional studies are also being carried out under the Canadian Transportation Fuel Cell Alliance's Studies and Assessments working group. A C$1.3 million budget supports studies such as the *Electrical Capacity in Canada* to assess the supply of electricity that will be available for electrolysis as a fuelling pathway to hydrogen in Canada; the *Policy/Economic Analysis* to assess the current economics of seven off-board hydrogen fuelling pathways and examine externalities such as health and air quality impacts, and determines what policy tools would be most appropriate in enabling these technologies to better compete with the current economics of gasoline and diesel; and, the *Market Research Study* in conjunction with the University of California Davis, which concentrates on fuel cell and hydrogen market analysis and hydrogen fuel station and distribution infrastructure.

In Japan, a *Policy Study Group for Fuel Cell Commercialisation*, which consists of various members from industry, academic and public organisations, was established in December 1999. Following several studies and the March 2001 Fuel Cell Commercialisation Conference, a strategy emerged for the practical application and implementation of fuel cell technologies. The strategy is based around a three-stage commercialisation plan through 2020, which integrates the development of fuel cell, hydrogen production, transportation and storage technologies concurrently with the implementation of demonstration programs, vehicle sales, construction of refuelling infrastructure, establishment of codes and standards, and a general push to enlarge the consumer market for stationary fuel cells and fuel cell vehicles. Taken together, and building upon the foundations laid

by *WE-NET*, this policy development work is now guiding one of the most ambitious and comprehensive HFC initiatives in the world.

The US *National Hydrogen Energy Roadmap* (November 2002), describes the principal challenges to be overcome and suggests ways the US can achieve the national vision for hydrogen. The *Roadmap* stresses the need for parallel development of model building codes and equipment standards to enable technology integration into commercial energy systems, along with outreach programs to effectively educate local government officials and the public, who will determine the long-term acceptance of these technologies. The *Roadmap* drew upon the earlier (February 2002) *National Vision of America's Transition to a Hydrogen Economy – to 2030 and Beyond*, which outlined a vision for America's energy future powered by clean, abundant hydrogen. This vision document was considered a first step to be used to evaluating hydrogen a long-term solution to America's energy needs. The efforts of 53 business executives, Federal and State energy policy officials, and leaders of universities, environmental organisations, and National Laboratories contributed to the development of the vision document.

Reported work on policy development in Europe includes Norway, where the government established a national Hydrogen Committee to define national targets to develop hydrogen as energy carrier, identify means and instruments for added value and better environment, identify necessary participation from government and framework conditions, and propose organisation, responsibility and necessary funding for a national hydrogen program.

In Germany, a new *Vision on Hydrogen Technologies* is currently being drawn up by an advisory council consisting of representatives of different ministries, industry and academia. The council has been called up by the Federal Ministry of Economics and Labour (BMWA). Hydrogen and fuel cells are addressed by the *Federal programme on energy research and energy technologies* as major topics for R&D.

Belgium is conducting policy studies on trends in vehicle and fuel technologies and a sustainability evaluation of technologies and modes in the transport sector in Belgium. Work at the Joanneum Research Centre in Austria is studying policy measures, incentives, and environmental impact evaluations on a life-cycle basis for the use of hydrogen as energy carrier. In Spain, the *Spanish Plan for Scientific Research, Technological Development and Innovation (2004-2007)* will consider hydrogen energy and fuel cells as separate items included in the priority devoted to renewable energies and emerging technologies. Other, more technical policy studies, include a technical-economical feasibility analysis of hydrogen in autonomous energy generating systems (HSAPS project), carried out by Trama Tecnoambiental Company.

The UK has also undertaken considerable work in the development of big-picture, guiding policy. For instance, the *Technology Roadmap* suggested actions and targets based on published benchmarks for major fuel cell development programs around the world as well as in the UK. A set of development targets was established with the objective of giving the UK a competitive position in certain fuel cell markets. Additionally, the *Review of UK Fuel Cell Commercial Potential* provided an assessment of the main applications for fuel cells, the drivers for fuel cells in these areas and the fuel cell technologies likely to be chosen. The UK's *Energy White Paper* sets out a strategy for the long term, giving industry the confidence to invest in a truly sustainable energy future. The paper commits to cutting CO_2 emissions by 60% by 2050 and notes the need/potential of fuel cells to play a greater part in the economy – initially in static form in industry or as a means of storing energy, but increasingly in transport. The paper sets the goal that hydrogen will ultimately be generated primarily by non-carbon electricity. Finally, the *Fuel Cell Vision Paper* notes that the UK should take a leading role in the development and deployment of fuel cells, and sets out various scenarios

for the short, medium and long term. Additionally, it specifies various R&D focus areas and mechanisms for the government to influence the development of the industry.

In Turkey, a number of policy studies have been undertaken including revising energy laws to meet European norms.

Policy Program Targets

The following section provides an overview of the forward-looking programs, policies and targets for IEA member countries responding to the HCG survey.

Australia

Australia recognises the potential of hydrogen to contribute to a more environmentally friendly and sustainable energy mix and plays an active role in the national and international development of hydrogen technologies. In doing so, Australia will focus on areas where it has resource, scientific and technical background. Neither the national hydrogen study nor the Australian government's energy White Paper specifies the adoption of any targets for hydrogen use. The government's view is that the market will determine how and when hydrogen will enter the energy mix, recognising that there are a range of energy options available to Australia. The expected emergence of a market for fuel cells in portable appliances is a good example of how this will occur without the need for any government mandates. The key issue is to promote and encourage adaptation to developments that are arising as a result of policy and technological change. Where there is a role for governments, it is in aiding industry to capture the opportunities that will emerge by ensuring that any barriers to doing so are removed or reduced. It is assumed that the main potential end uses for hydrogen for Australia in the period to 2050 will be road transport portable electrical appliances and distributed generation.

Austria

Concerning forward-looking hydrogen pathways, Austrian research institutions are mainly interested in hydrogen production from renewable energy sources (from biogas, biomass and PV/electrolysis). In 2001-2002 a fuel cell strategy both for stationary and mobile/portable applications was formulated. For mobile applications, the plans include: taking advantage of Austria's excellent position in mechanical engineering through the development of suitable balance-of-plant components and adequate production technologies; further improvement of the strong position in the field of electromotive drive units; establishing "centres of excellence" concentrating on PEM fuel cells with circulating electrolytes and SOFC; research in the field of APUs; and development of novel vehicles architectures and concepts. The Federal Ministry of Transportation, Innovation and Technology (BMVIT) has now implemented strategy elements in two new R&D program lines: (1) the *Austrian Advanced Automotive Applications* project; and, (2) *Energy Systems of Tomorrow*. Concerning hydrogen as energy carrier, Austria is currently in the process of developing a new strategy, most likely to be finished by the end of 2004.

Belgium

Although there is no specific national R&D program, Belgium is working on a number of individual projects to explore the potential of hydrogen and fuel cells. Additionally, two policy studies are under way: the development of tools to evaluate the potential for sustainable hydrogen in Belgium; and, an initiation to the future of the energy situation in Flanders in 2050, in which hydrogen will have a role.

Canada

The vision of the national program is to strengthen and enhance Canada's leadership position in the supply and demand for renewable and sustainable energy from fuel cells and hydrogen – with the ultimate goal of accelerating the commercialisation of Canadian fuel cell and hydrogen products for Canada and the world. Canada's program targets are delineated in 3 phases:

- Phase 1: RD&D and Early Deployment (0-5 years) – RD&D that supports industry's pre-commercial efforts such as testing prototypes. Work will focus on number of elements, including: (1) bringing down the cost of units; (2) beginning the development of a hydrogen supply infrastructure; (3) establishing programs to support commercialisation (market demonstration and government first purchase); (4) load building across all applications (stationary, portable and mobile); (5) leading the development and implementation of international codes and standards for hydrogen safety; (6) educating professionals and technical staff including: engineers, researchers, educators, technologists and mechanics; (7) establishing policy measures (fiscal and regulatory); and, (8) increasing public awareness of the benefits of hydrogen and increase confidence in safety and performance.
- Phase 2: Broad Based Deployment (5-10 years) – will seek to work with industry and all levels of government to review and re-evaluate overarching strategy based on findings of first five-year period; re-allocate funding and emphasis if necessary; continue with demonstration projects and showcasing of new technologies; implement new policy measures (fiscal and regulatory), such as buy-down programs for emerging technologies; and, expand hydrogen supply infrastructure to allow for inter-city commuting.
- Phase 3: Market Expansion (10-20 years) – work will seek cost reductions of fuel cells through the development of large-scale manufacturing (mass production); continue hydrogen supply infrastructure development on a national level; refinement of policy measures (fiscal and regulatory); and, continue support of RD&D in areas of new advancements in hydrogen and fuel cells.

On October 9, 2003, the Government of Canada announced a C$215 million investment that will capitalise on the use of hydrogen and fuel cells. The investment is directed by three strategic priorities:

- Early adoption of hydrogen technologies through integrated demonstration projects undertaken by partnerships that will showcase a working model of the hydrogen economy in real-world settings;
- Improved performance and reduced costs of hydrogen technologies, and extension of Canadian leadership through research and development of innovative new applications in strategic areas of the hydrogen value chain; and
- Initiatives to establish a hydrogen infrastructure through Sustainable Development Technology Canada, building on the foundation's success in establishing successful, partnership projects.

Accelerating the development, commercialisation and early adoption of hydrogen technologies and applications in Canada is a key element of these investments. The Government of Canada will partner with eligible recipients to demonstrate these technologies and to integrate them into a comprehensive working model of the hydrogen economy. This includes fostering clusters of expertise and partnerships in the form of real-world "hydrogen villages." As part of this, Industry Canada and its partners, such as Technology Partnerships Canada and the National Research Council, will

dedicate more than C$85 million to hydrogen economy efforts, advancing the work already underway and increasing hydrogen activity across industry.

Denmark

The Danish national research strategy for developing fuel cells concentrates on SOFC and PEM technologies and includes the following objectives:

- To maintain and develop Danish R&D at highest international position.
- To involve Danish industry in this development.
- To assure internationally competitive Danish products in terms of price, durability, environmental and technical feasibilities.
- To bring the products to the market.
- To orient R&D on fuel cells towards possible applications in Denmark and elsewhere.
- To educate researchers, technicians, engineers in the field.
- To maintain and build Danish know-how through active patenting.

A national RD&D strategy for hydrogen technologies is under preparation and will be finalised in the first part of 2005.

Finland

The hydrogen strategy is to focus on distributed hydrogen-related energy systems, network with international activities (EU, IEA, Nordic), and connect with fuel cell activities in Finland. Finland's fuel cell strategy is a bit more developed, with plans to focus on fuel cell systems demonstrations and applications. Finland also plans to build a close relationship with industry, creating a national fuel cell group, and networking with international fuel cell activities. Program activities include improving the overall performance of fuel cell technologies and developing the DENSY (Distributed Energy Systems) program with the goal to grow the export income of Finland.

France

The main objectives in France's future work program will be focused on massive applications in the transport sector and intermediate markets in stationary applications. These plans include:

- Clean production of hydrogen – thermochemistry and steam electrolysis combined with future high-temperature nuclear reactors and biomass.
- Storage of hydrogen – high pressure storage and new types of storage for portable applications, carbon nanostructures.
- PEM fuel cells – continue work on components (electrolyte, electrodes, bipolar plates), systems (modelling and design) and phenomenology (thermohydraulics). Study and development of micro-cells for portable applications.
- SOFC fuel cell – continue work on components and stack development.

- Transverse studies for the acceptability and credibility of a future hydrogen economy (technology watch, techno-socio-economic studies, safety, etc.).

Notably, France's Petroleum Institute (IFP) and the Atomic Energy Commission (CEA) will contribute to the *Hyfrance* project, whose main goal is to build a hydrogen roadmap for France.

Germany

Germany is at the forefront of hydrogen and fuel cell technology development and implementation worldwide, with a number of federal and regional initiatives already in place. There are numerous co-operations between public and private enterprises, such as the development of the MCFC technology for stationary application and the demonstration of the NEBUS and Citaro fuel cell buses from DaimlerChrysler. Other examples are the *Clean Energy Partnership* in Berlin, an initiative of the Federal Ministry of Traffic, Building and Housing (BMVBW) for demonstrating a hydrogen service station and hydrogen powered vehicles. Another key initiative is the so-called Transport Energy Strategy (TES) for the introduction of a new energy carrier to the transport sector.

Within the Federal Programme for "Energy Research and Energy Technologies" (Energy Research Programme) the Federal Ministry of Economics and Labour (BMWA) supports research, development and demonstration of fuel cells and hydrogen technologies. Intensive RD&D on hydrogen technologies was started in Germany in 1988, and concentrated on the development of specific technologies like hydrogen production using electrolysis, hydrogen storage, and larger projects to demonstrate the complete supply chain of a solar hydrogen energy economy (HYSOLAR and the Solar-Hydrogen-Bavaria Project BAYSOLAR). This work was concluded in 1995/1999 with the result that in principle the main components of a hydrogen energy system were developed and functioning, however, that commercial viability of a solar hydrogen economy could only be reached in the far future. As a consequence, since 1995 RD&D concentrated on fuel cells and was supported by an annual BMWA budget of €8-10 M per year. Ambitious projects concentrating on new materials, improved components and system integration have been supported.

The "Programme on Investment into the Future" (ZIP) was initiated in 2001 as part of the Energy Research Programme with the main priorities of fuel cell development and demonstration. Some projects related to hydrogen technology, such as demonstration of infrastructure for fuel cell buses are included in this programme. Within ZIP more than 40 additional projects are being funded by BMWA. Several 250 kW MCFC projects, one plant with SOFC tube concept technology, and several PEMs (2-5 kW) for house applications are in operation or in a planning phase. Projects for the demonstration of fuel cell buses (Stadt Barth, Berlin) and the development of a fuel cell car (AUDI) are also included. Under the EU CUTE project the demonstration of hydrogen infrastructure for the DaimlerChrysler fuel cell bus NEBUS/Citaro is being co-financed within ZIP.

"The Clean Energy Partnership" is an alliance between the BMVBW and nine companies including car manufacturers BMW, DaimlerChrysler, Ford, MAN, Opel, the Berlin Transit Agency, gas supplier Linde, and ARAL. The partnership aims to demonstrate the usability of hydrogen as a transportation fuel. The project will last four years during which a hydrogen filling station will be constructed by Germany's major motor fuel distributor ARAL.

Other noteworthy programmes include Bavaria's "Hydrogen Initiative" and the North-Rhine Westphalia "Hydrogen and Fuel Cell R&D Programme" both being funded at a rate of €7-10 million per year. In 2003, BMWA established an advisory council on hydrogen technologies with the objective to draw up a new vision on future R,D&D demand.

Greece

Although Greece has no specific national plan on hydrogen and fuel cells, the topics have recently been included in the national research agenda. Priorities and targets have recently been set and the government is launching a framework for the collaboration of Greek research institutes with established players in the R&D field, namely Australia, Canada, Japan and the US. The Greek R&D community, in collaboration with government, is developing the concept of "hydrogen islands", with the objective of developing applications for the niche market of Greek islands that are non-grid connected, but also applicable to other remote communities in Europe.

Italy

The following areas have been identified as priorities for hydrogen as a sustainable energy carrier in Italy:

- Develop technologies, components and innovative systems for hydrogen production from renewable sources or from fossil fuels with CO_2 separation.
- Develop systems for hydrogen storage.
- Study CO_2 sequestration in geological sites and development of related technologies.
- Develop technologies, components and systems for use of hydrogen in transport sector and for energy distributed generation.
- Improve performances and cost reduction through the development of innovative materials, components and cell design.
- Develop and demonstrate fuel cell systems for transportation, stationary power generation and portable units.
- Plant demonstration, monitoring and verification of operative behaviour of cells using different fuels.

The following targets have been established for development work on MCFCs:

	Current Status	Objective of Demo Phase	Long-term Commercial Target
Stack Life (hours)	> 12,000	≥ 30,000	≥ 40,000
Electrical Efficiency (%)	≥ 47.0	≥ 49.0	≥ 55.0
Efficiency Using Cogen (%)	≥ 80.0	≥ 80.0	≥ 80.0
Decay Rate (% mV/1,000 h)	1.0	< 0.5	< 0.2
Production Cost (€/kW)	≥ 5,800	≤ 2,300	1,200

The following targets have been established for development work on PEMs:

	Objectives of Demo Phase		Long-term Commercial Target	
	Stationary	Transport	Stationary	Transport
Stack cost, (€/kW)	1,000	100	300	30
System cost, (€/kW)	3,000	150	1,000	50
Durability, (hours)	10,000	2,000	40,000	5,000

Japan

As delineated by Japan's *Policy Study Group for Fuel Cell Commercialisation*, the country's fuel cell development strategy is based around a three-stage commercialisation plan through 2020, which integrates the development of fuel cell, hydrogen production, and hydrogen transportation and storage technologies, concurrently with the implementation of demonstration programs, vehicle sales, construction of refuelling infrastructure, establishment of codes and standards, and a general push to enlarge the consumer market for fuel cells and fuel cell vehicles.

According to Ministry of Economy, Trade and Industry's (METI) commercialisation strategy, 2002-2005 will focus on continued technology development, vehicle and stationary fuel cell demonstrations, development of soft infrastructure and codes & standards, and the establishment of fuel standards; 2005-2010 is to be the Introduction Stage, when the introduction of vehicles will be accelerated along with the gradual establishment of the fuel supply system. Finally, the Diffusion Stage will encompass initiatives taken forward from FY2011, particularly the establishment of fuel supply system and "self-sustained growth" driven by private sector promotion and adoption.

Fuel cell performance targets:

Fuel Cell Vehicles	Stationary Fuel Cells
Stack: Power generation efficiency over 55-65% (LHV-HHV)	**Stack:** Power generation efficiency over 55%
Cost: below 5,000 yen/kW	**Cost:** Home use below 300,000 yen/system; business use below 150,000 yen/kW
Hydrogen storage: 5 kg on vehicle hydrogen storage (over 500 km cruising)	

Commercialization targets which will drive the strategy through 2020:

By the end of the *Introduction Stage* in 2010:

- 50,000 fuel cell vehicles,
- 2.2 GW of stationary fuel cell co-generation systems.

By the end of the *Diffusion Stage* in 2020:

- 5,000,000 fuel cell vehicles,
- 4,000 hydrogen stations,
- 10 GW of stationary fuel cell co-generation systems.

○ Korea

The Korean Government announced a very ambitious plan to replace 5% of the national energy consumption by new and renewable sources of energy (NRSE). Currently the percentage of NRSE in the national energy consumption is 2 percent. Along with this announcement, Hydrogen and Fuel cell was selected as one of 10 economic growth areas for the future. To fulfil the national strategy, two government ministries, MOCIE (Ministry of Commerce, Industry and Energy) and MOST (Ministry of Science and Technology) are deeply involved. For example, MOCIE established the *National RD&D Organisation for Hydrogen and Fuel Cell Programme* for overcoming barriers to the commercialisation of fuel cells. The program budget is US$466 million for 8 years from 2004. The RD&D program includes:

- 250 kW MCFC module system development by 2008.
- 80 kW PEMFC development for passenger vehicle by 2008.
- 3 kW PEMFC system development for RPG by 2005.
- SOFC (< 5 kW) system development for RPG and APU by 2008.
- 50 W DMFC system for mobile application by 2006.
- Hydrogen internal combustion engine development.
- Hydrogen storage: nano carbon material.
- Hydrogen station development and demonstration.
- Code and standard development.

MOST concentrates its R&D efforts on the development of fundamental technologies for hydrogen and fuel cells. The *21st Century Frontier Hydrogen R&D Program* was established to develop hydrogen production and storage technologies. A fundamental technology development program for PEM, SOFC, DMFC and next generation fuel cells has also initiated as part of the programme. Eliminating barriers to the commercialisation of fuel cell, such as reliability and cost, is the main target. The combined budget for the two programs reaches US$120 million for the next 8 years from 2004. These programs include:

- The development of an efficient prototype hydrogen production system, utilising water-splitting technologies (photocatalytic/thermochemical, NRSE sources, etc.) by 2012.
- The development of high-purity hydrogen production/supply system utilising fossil fuels such as natural gas/LPG/methanol/naphtha, etc. by 2012.
- Hydrogen storage: high pressure cylinder (700 bar), cryogenic technology, metal and chemical hydride.
- PEM: high temperature membrane, low catalyst loading, high performance MEA.

- DMFC: low methanol permeability membrane, high performance catalyst.
- SOFC: new oxide electrolyte, interconnector materials.

Korean Targets for 2012:

Classification	Phase 1 ('03-'05) R&D	Phase 1 ('06-'08) Demonstration	Phase 1 ('09-'12) Dissemination
Hydrogen station	1	10	50
Fuel cell vehicle	Passenger car: 10 Bus: –	Passenger car: 100 Bus: 10	Passenger car: 10,000 Bus: 500
Distributed power by fuel cell	Cumulative 300 units (250-1,000 kW)		
Building	Cumulative 2,000 units (10-50 kW)		
RPG	Cumulative 10,000 units (less than 3 kW)		

Netherlands

The Netherlands expects to continue general R&D on hydrogen and fuel cells, including participation in a number of EU programs: EU CUTE project (Bus project); EIHP (codes & standards); NaturalHy (H2 mixtures in natural gas); FRESCO Scooter project; Policy Studies on infrastructure and transition management activities; and, fuel Cell RD&D activities. Under the country's Energy Research Strategy (EOS) preparatory projects have been delineated to achieve industrial efficiency improvement and to launch pilot projects covering areas such as transition to hydrogen and CO2 sequestration.

Norway

The Norwegian government has established a national Hydrogen Commission to define national targets to develop hydrogen as an energy carrier, identify means and instruments necessary participation from government and framework conditions, and propose organisation, responsibility and funding for a national hydrogen program. The Commission delivered their report to the Minister of Petroleum and Energy and the Minister of Transport in June 2004, establishing four target areas for a national hydrogen initiative:

- Environmentally friendly production of hydrogen from Norwegian natural gas.
- Early users of hydrogen.
- Hydrogen storage development.
- Development of a hydrogen industry.

The Commission also proposed a 10-year programme focusing on R&D and HFC demonstrations with an overall budget of €120 million.

Spain

In Spain, there is not presently a specific programme devoted to hydrogen energy and fuel cells, however, the Spanish Plan for Scientific Research, Technological Development and Innovation (2004-2007) considers these topics as specific work items within programmes devoted to developing renewable energies and emerging technologies. In this context, Spain has developed a strong wind energy industry that is working on hydrogen as an energy storage means for better utilising wind energy resources. Likewise, vehicle component manufacturers are working on fuel cell component manufacturing and integration as possible new business development – as a consequence, an incipient industry of manufacturing MEAs for PEM (including new patent for the membrane) and PEM fuel cell stacks is emerging.

Sweden

The Swedish National Energy Agency is the main governmental actor in both the fields of hydrogen and fuel cells. The Agency has established a program for fuel cells but not yet for hydrogen. The overall budget is set to some 4 M€ including all efforts from the Agency. A large part of the funding focuses on specific projects related to the development of polymer fuel cells for transport applications but also for stationary use, with a large involvement of industries and energy utilities. The on-going phase covers activities up to the end of 2005. A long-term government-funded hydrogen project deals with reforming hydrogen and oxygen from water with solar energy through artificial photosynthesis. The energy company Sydkraft has built a hydrogen fuelling station which also provides hydrogen and natural gas mixture for fuelling buses in Malmö (south Sweden). The project will last for two years and aims to demonstrate that hydrogen is already available for energy use, although still too expensive.

Switzerland

Swiss present and future policy attempts to identify target activities rather than support a large spectrum of widespread and dispersed projects. Government policy will focus on hydrogen production using renewable energy, storage and distribution logistics (high pressure technology, fast filling, etc.). Considerable attention is given to testing and developing novel materials and devices serving different functions along the whole hydrogen supply/production/utilisation chain. Fuel Cell activities address SOFC- and PEM-systems supplied with natural gas, biogas or hydrogen.

Switzerland's Hydrogen Commercialisation plan includes:

- Demonstration: now – 2030.
- Market Introduction: 2015-2050.
- Market Penetration 5% of Energy use: from 2060 on.

Turkey

Turkey signed an agreement with the United Nations Industrial Development Organization (UNIDO) to build a $40 million International Centre for Hydrogen Energy Technology (ICHET). UNIDO's project is aimed at transferring existing hydrogen technologies from Turkey to other developing countries to help them to catch up with the developed world in the field of renewable

energy resources. The main objective of ICHET will be to further the advancement of applied research and development on hydrogen energy and to stimulate applications in industrial development throughout the world in general – and particularly in developing countries. The areas of work will include hydrogen energy policy, economics, production, storage, utilisation techniques and other related studies. ICHET will be established within the legal framework of UNIDO as a scientific institution headquartered in Istanbul with the operational autonomy.

Since about 64% of world boron reserves are found in Turkey, scientific studies on boron have been conducted to investigate the potential of boron as a hydrogen carrying material in fuel cells. Turkey is planning to upgrade the utilisation of this natural source and is inviting researchers, investors and international organisations to cooperate in the programme.

United Kingdom

The UK Fuel Cell Vision Paper sets out the following scenarios for the development of the domestic HFC industry:

- Short term: Work during 2003-2007 will focus on demonstrations to prove the economic and technical feasibility of HFC technology, establish carbon reduction potentials and foster the development of early hydrogen infrastructure. Demonstrations are planned to be an important part in increasing awareness of fuel cells and the benefits that they can bring. This work is to be complementary with awareness raising initiatives. Building on this Vision, the Government will develop a clear policy framework for fuel cells in order to provide long-term continuity and a context in which industry can flourish.

- Medium term: Work during 2008-2012, will see value move downstream, and as a consequence, systems integration and other support will be of increasing prominence. Research will continue to focus on long-term challenges in areas such as next generation materials, fuels and fuel processing, integration and manufacturing and automation technologies. Structured and targeted training will help to ensure that skills needs are met.

- Long term: Work during 2013-2023, will see a shift in emphasis towards a much wider spectrum of commercial fuel cell applications, with a diminishing requirement for government intervention. The market will be increasingly consumer driven, and a high proportion of the population will have first-hand experience with fuel cells. Hydrogen infrastructure will continue to grow through the period to support the widespread application of fuel cells (including significant car penetration). Renewables will play an increasingly prominent role. Codes and standards will be revised and updated to reflect new developments. Demonstrations will be driven and funded by industry for incremental improvement

Furthermore, the UK White Paper sets out a long-term strategy to give industry the confidence to invest in a truly sustainable energy future. The paper commits to cutting carbon dioxide emissions by 60% by 2050 and notes the need/potential of fuel cells to play a greater part in the economy – initially in static form in industry or as a means of storing energy, but increasingly in transport. The paper sets the goal that hydrogen will ultimately be generated primarily by non-carbon electricity.

United States

Throughout the planning process US DOE has envisioned a phased transition to a hydrogen economy, each of which requires and builds on the success of its predecessor:

- In Phase 1 government and private organisations will research, develop, and demonstrate "critical path" technologies and safety assurance prior to investing heavily in infrastructure. Public education and codes and standards are to be developed concurrently with the RD&D. The President's Hydrogen Fuel Initiative is consistent with completion of the critical path technology RD&D phase leading up to a commercialisation decision in 2015. This Phase could continue beyond 2015 to support basic science and to further develop advanced, sustainable technologies for hydrogen production and use. The commercialisation criteria will be based on the ability of hydrogen fuel technology to meet customer requirements and to establish the business case.

- Phase 2 is the Initial Market Penetration Phase. This could begin as early as 2010 using existing natural gas and electric grid infrastructure for applications such as portable power and some stationary and transportation applications; it will continue as hydrogen-related technologies meet or exceed customer requirements. As markets are established, this leads to Phase 3, or the Infrastructure Investment Phase, in which there is expansion of markets and infrastructure.

- The start of Phase 3 is dependent on a positive commercialisation decision for fuel cell vehicles in 2015. A positive decision will attract investment in infrastructure for manufacturing fuel cells and for producing and distributing hydrogen. Government policies still may be required to nurture this infrastructure expansion phase.

- Phase 4, which could begin around 2025, is the Fully Developed Market and Infrastructure Phase. In this phase, consumer requirements will be met or exceeded, national benefits in terms of energy security and improved environmental quality will be achieved, and industry will receive adequate return on investment and compete globally. Phase 4 provides the transition to a full hydrogen economy by 2040.

Specific targets and objectives for hydrogen production and delivery include:

- By 2010, reduce the cost of distributed production of hydrogen from natural gas and/or liquid fuels to $1.50/kg (delivered, untaxed) at the pump (without carbon sequestration).

- By 2010, develop and demonstrate technology to supply purified hydrogen (purity sufficient for polymer electrolyte membrane (PEM) fuel cells) from biomass at $2.60/kg at the plant gate (projected to a commercial scale 75,000 kg/day). The objective is to be competitive with gasoline by 2015.

- Develop advanced renewable photolytic hydrogen generation technologies. By 2015, demonstrate an engineering-scale biological system that produces hydrogen at a plant-gate cost of $10/kg projected to commercial scale. By 2015, demonstrate direct photoelectrochemical water splitting with a plant-gate hydrogen production cost of $5/kg projected to commercial scale. The long-term objective for these production routes is to be competitive with gasoline.

- By 2010, verify renewable integrated hydrogen production with water electrolysis at a hydrogen cost of \$2.50/kg (electrolyser capital cost of \$300/kWe for 250 kg/day with 73% system efficiency). By 2010, verify large-scale central electrolysis at \$2.00/kg hydrogen at the plant gate.
- By 2015, research and develop high-and ultra-high-temperature thermochemical/electrical processes to convert hydrogen from high temperature heat sources (nuclear or solar) with a projected cost competitive with gasoline.
- Evaluate other new technologies that have the potential for cost-effective sustainable production of hydrogen and fund appropriate research and development (R&D) in promising areas.

Specific targets for developing and demonstrating viable hydrogen storage technologies for transportation and stationary applications:

- By 2005, develop and verify on-board hydrogen storage systems achieving 1.5 kWh/kg (4.5 wt%), 1.2 kWh/L, and US\$6/kWh.
- By 2010, develop and verify on-board hydrogen storage systems achieving 2 kWh/kg (6 wt%), 1.5 kWh/L, and US\$4/kWh.
- By 2015, develop and verify on-board hydrogen storage systems achieving 3 kWh/kg (9 wt%), 2.7 kWh/L, and US\$2/kWh.
- By 2015, develop and verify low cost, off-board hydrogen storage systems, as required to support transportation, stationary and portable power markets.
- By 2015, develop and verify vehicle interface technologies for fuelling on-board hydrogen storage systems.

Specific targets for the development of fuel cell power system technologies for transportation, stationary, and portable applications:

- Develop a 60% efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of \$45/kW (including hydrogen storage) by 2010 and \$30/kW by 2015.
- Develop a 45% efficient reformer-based fuel cell power system for transportation operating on clean hydrocarbon or alcohol-based fuel that meets emissions standards, a start up time of 30 seconds, and a projected manufactured cost of \$45/kW by 2010 and \$30/kW by 2015.
- Develop a distributed generation PEM fuel cell system operating on natural gas or propane that achieves 40% electrical efficiency and 40,000 hours durability at \$400-\$750/kW by 2010.
- Develop a fuel cell system for electronics with an energy density of 1,000 Wh/L by 2010.
- Develop a fuel cell system for auxiliary power units (3-30 kW) with a specific power of 150 W/kg and a power density of 170 W/L by 2010.

The European Union (EU)

Many EU countries have been among the most active worldwide in developing the technologies and concepts for the commercialisation of hydrogen and fuel cells. The EU is seeking to promote greater cooperation, pooling of resources and harmonisation of efforts. The goals are the reduction of greenhouse gas emissions in order to meet the EU's Kyoto Protocol commitments, improve the security of energy supply, and promote industrial competitiveness. The long-term EU vision is to have in place an energy supply system based on renewable energies and fuel cells with hydrogen and electricity as prominent energy carriers within 20-30 years *(More information on EU HFC programmes can be found in PART 2 – See European Union Profile)*.

Nordic energy research

Nordic Energy Research Programme is a Nordic institution under the Nordic Council of Ministers and is funded by the Nordic Governments. In the area of hydrogen for the energy sector, €2.3 million have been allocated to six HFC projects, including demonstration projects in Denmark, Finland, Norway, and Sweden. More information can be found at: *www.risoe.dk/nei/*

- *Biohydrogen* (Roskilde University (DK), University of Jyväskyla (FIN), Tampere University of Technology (FIN), University of Akureyri (IS), Norwegian Institute of Water Research (N), University of Uppsala (S), Linköbing University (S)).
- *Hydrogen Production* – electrolysis (Risø National Laboratory (DK), Helsinki University (FIN), University of Oslo (N)).
- *New Metal hydrides for hydrogen storage* – (Technical University of Denmark (DK), Helsinki University of Technology (FIN), University of Iceland (IS), IFE (N), University of Oslo (N), Uppsala University (S), Stockholm University (S)).
- *NORSTORE* (advanced hydrogen storage materials and their integration) (Technical University of Denmark (DK), Helsinki University of technology (FIN), University of Iceland (IS), IFE (N), Studsvik Neutron Research laboratory (S)).
- *Nordic and Baltic Applied Fuel cell network* (Technical University of Denmark (DK), IFE (N), Statkraft (N), Kgl. Tekniska Högskolan (S)).
- *Nordic Hydrogen Energy Foresight* (Risø National Laboratory (DK), Energi E2 (DK), IRD Fuel Cells (DK), DGC (DK), IDA (DK), VTT (FIN), Wärtsilä (FIN), Fortum (FIN), ABB (FIN), University of Iceland / Icelandic New Energy (IS), NTNU / SINTEF (N), Norsk Hydro (N), Swedish Defence Research Agency (S), Vattenfall (S), AGA (S), Swedish Hydrogen forum (S)).

Chapter 6. PUBLIC EDUCATION

Awareness of hydrogen and fuel cell applications remains low and represents a major non-technical barrier to overall technology adoption. A necessary element of hydrogen and fuel cell education programs is to achieve a level of awareness of hydrogen's benefits among educators, key target audiences, and the public, while supporting the creation of a skilled and informed workforce required for a hydrogen future.

Overview of IEA Government public education activities

Very few governments reported work in the area of public education. The US program is the most comprehensive, with US$5.7 million in 2004 funding. The *Hydrogen, Fuel Cells & Infrastructure Technologies Program* includes a subprogram to accomplish the overall objective of educating target audiences about the long-term benefits and near-term realities of hydrogen, fuel cell systems, and related infrastructure. Education activities will rely on internet-based materials to the greatest extent possible. Building the *Hydrogen, Fuel Cells & Infrastructure Technologies Program Web site*, creating a library of hard-copy educational materials and a distribution system will comprise initial priority activities. The information dissemination infrastructure will provide users and program partners nationwide with quick and easy access to educational materials. Initial education efforts will focus on teachers and students, state and local governments, and large-scale end-users-target audiences identified as critical to the successful implementation. Safety and code officials are also top priority audiences. Educational activities to serve their needs will be conducted in conjunction with the *Safety and Codes and Standards subprograms*.

Canada's *Early Adopters* program also includes educational work elements which will enable firms to showcase their technologies in working pilot-scale of a hydrogen economy and will help increase investor and consumer awareness of Canadian capabilities and of the many benefits and uses of hydrogen-powered applications.

The Swiss *Hydrogen Energy Program* is divided into four segments, one of which supports activities such as the development of educational materials and devices, practical demonstrations of hydrogen technologies and public-awareness building activities.

Germany's *Programme on Investment into the Future* also includes a section on training and education. Three training and education centres have been established in Germany and are now in operation. They address different target groups, from students to engineers. Work at the centres includes the development of suitable education materials. Germany reports that technology demonstrations can be a valuable educational tool, and the Bavarian Hydrogen and Fuel Cells exhibition is part of the Germany's educational outreach plan. Moreover, public relations have been one topic in the work plan of public funded demonstration projects.

The UK *Fuel Cell Vision Paper* also focuses on demonstrations to prove the economic and technical feasibility of fuel cell technology and build awareness of fuel cells benefits. Also, the government-sponsored *Low Carbon Vehicle Partnership (LowCVP)* will ensure that UK industry is fully involved in the shift to low-carbon transport, providing a forum for all stakeholders to work towards this goal.

PART 2

COUNTRY PROFILES

Australia

- ***HFC work driven by the government's broader objectives of reducing the greenhouse gas intensity and developing national clean coal strategy.***
- ***Focus on ensuring that the appropriate codes and standards are put in place.***
- ***MCFCs work for small scale stationary applications for remote areas in Australia.***
- ***Considerable work on general research on fuel cells, materials and components.***
- ***Highlight: Trial and demonstrations of three hydrogen PEM fuel cell buses in Perth.***

Overview

In its energy *White Paper*, released in June 2004, the Australian government recognised that the country should be prepared for a possible transition to a hydrogen economy in the long term, and that there will be significant opportunities and challenges associated with such a transition. In particular, the government understands the importance of maintaining a close interest in the development of international codes and standards for the hydrogen economy in order to ensure that these do not inhibit Australian participation or uptake of new technologies.

Hydrogen R&D initiatives, under way in Australia are largely associated with broader government programs and other policy initiatives. These support, for example, Australia's participation in bodies such as the International Partnership for the Hydrogen Economy as well as the country's participation in established forums such as the IEA and APEC. At the national level, research and development into hydrogen is occurring in a number of universities as well as through *Energy Transformed*, a significant, wide-ranging and long-term initiative of the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia's premier public sector research institution. Through CSIRO, a comprehensive review of Australian hydrogen and fuel cell technology projects is being compiled, and this is expected to be completed before the end of 2004.

Australia is an example of where support for HFC R&D is consistent with the government's broader objective of reducing the greenhouse gas intensity of energy supply and use. In addition to any eligibility that HFC projects may enjoy through generally available measures, HFC work is an element of Australia's *COAL21* program which includes research into hydrogen production by coal gasification (and employing carbon sequestration) as part of the national clean coal strategy.

Priorities and targets

Australia notes that in addition to researching and developing the technologies that underpin the use of hydrogen and fuel cells, there are a number of infrastructural issues that require early attention. These include ensuring that the appropriate codes and standards are put in place and coordinating them with codes and standards that are being developed and adopted internationally. Australia

proposes to play an active role in that process to ensure that codes and standards are not detrimental to Australia, especially in recognition of its ambitions to exploit its renewable and fossil resources for hydrogen production or to utilise hydrogen in any particular way. It is assumed that the main potential end uses for hydrogen in Australia in the period to 2050 will be: road transport, portable electrical appliances (for example portable computers and mobile phones), and distributed generation.

Program activities

Australia's support for HFC research occurs mainly through generally available measures. One project that has been funded is the refining of MCFC systems as part of a project to develop advanced system integration techniques and catalysts for internal reforming fuels cells. The aim is to enable a wide range of fuels to be used with MCFCs for small scale stationary applications suitable for remote areas in Australia. Other Australian programs look at the use of coal-gas, natural gas, and coal seam methane to produce hydrogen for use in fuel cells for transportation and co-generation.

Considerable work in the area of general research on fuel cells, materials and components was reported by Australia, where the government-sponsored fuel cell R&D program has made efficiency improvements in fuel cell electrodes by the formation of platinum nano-clusters in porous carbon by high density plasma sputter mechanisms. Initial experiments on the plasma sputter deposition of platinum onto a porous film has shown great promise and aggregates of platinum were detected in the film with a density profile which decreased away from the surface exposed to the plasma.

Australia's PEM work also concentrates on improving ceramic membranes formed from molecular sieve silicate materials, which feature 3 Å pore average, ideal for hydrogen separation from other gases such as CO_2, CO, N_2. These membranes can operate at high temperatures up to 400-50°C. The work focuses on the preparation of materials using sol gel methods. Additionally, general R&D in Australia looks at developing materials consisting of composite inorganic and organic polymers. The inorganic component is of proton conducting materials such as zirconium phosphate. The organic polymer is of proton-conducting materials such as Dupont's Nafion. The aim is to develop material that has high sustained proton conductivity at high temperatures, thereby reducing the requirement for CO removal from hydrogen fuel and making the PEM fuel cell system more robust.

R&D into large-scale, "zero-emission" coal gasification technology route for the co-production of electricity and hydrogen has gained significant momentum in Australia over the past few years. Mineral carbonation for the storage of CO_2 in a solid rather than gaseous form is also gaining R&D attention. Power generation using coal gasification combined with geological sequestration is expected to be able to reduce greenhouse gas emissions by about 80 per cent, compared with electricity generation without sequestration, but with an efficiency penalty of about 7 per cent.

Specific programs include:

- **Perth Hydrogen Bus Trial.** Trial and demonstrations of three hydrogen fuel cell buses. Evaluation of the potential benefits for the operation of bus services in Perth and elsewhere in Western Australia. Project partners include the Western Australian State Government, Murdoch University. BP, and Daimler-Chrysler working under a budget of $10.72 million (cash) $5 million (in kind).
- **The University of Queensland.** Development of the "ultra-commuter," an ultra light-weight, energy efficient, low-polluting, series-hybrid electric commuter vehicle. It will be partially powered by on-board solar cells, and a small scale (~ 10 kW) PEM. Australia's University of Queensland

is also working to develop a "Robust Remote Area Power Supply" system based on SOFC technology for small-scale applications up to 5 kW.

- **Hydrogen Energy Systems in Antarctica.** The project focuses on identification and analysis of the barriers and opportunities related to the use of hydrogen energy technologies in remote regions, including: (1) Detailed technical analysis of the potential role of hydrogen energy technologies in a number of energy use scenarios, and possible impact on performance, based on the Australian Antarctic Program. (2) Development of a strategy to effectively, efficiently and safely implement hydrogen energy technologies into Antarctic operations, and specific recommendations to overcome the key barriers. (3) Development of experiences and recommendations for the implementation of hydrogen energy technologies in other regions. (4) International expansion of the existing collaboration with IFE (Norway) via a researcher collaboration exchange in 2004 which will develop improved hydrogen energy systems.
- **Efficiency improvement of fuel cell electrodes** by the formation of platinum nano-clusters in porous carbon by high density plasma sputter mechanisms. The properties of thin films deposited from plasma are critically dependent on the flux, energy and charge state of the particles striking the growing surface. Research has established that it is only the energy of the species incorporated into the film that changes its bulk properties even if there is a high flux of non-incorporated energetic ions. Research will be applied to finding the deposition of a catalyst onto the electrode in a fuel cell. Initial experiments on the plasma sputter deposition of platinum onto a porous film with collaborators in Orleans has shown great promise and aggregates of platinum were detected in the film with a density profile which decreased away from the surface exposed to the plasma.

Key players

- Research is under way in Murdoch University, Queensland University, Melbourne University, the University of New South Wales, Griffith University and the Australian National University funded on a project basis through the Australian Research Council.
- CSIRO Energy Transformed Flagship.
- Ceramic Fuel Cells Limited.

The Australian fuel cells industry

Australian company Ceramic Fuel Cells Limited (CFCL) is a world leader in planar SOFC technology and plans to demonstrate units in 2004. It should be noted that CFCL also seeks to work with application development partners to create market-ready packages incorporating solid oxide fuel cells.

Other activities

- The Australian government and the University of Tasmania are constructing two large wind turbines at Mawson Base in Antarctica with the objective to supply the base's annual electricity requirements and to produce sufficient hydrogen for use as transport fuel.
- A research team at the University of New South Wales School of Materials Science and Engineering in Sydney, along with industry support, is investigating mechanisms for improving

the efficiency of hydrogen manufacture from water energized by sunlight using photo-sensitive materials, including the development of titanium-based photo-sensitive catalyzing electrodes.

- The University of Queensland is investigating hydrogen storage in carbon nanotubes, and Griffith University is working on degradation mechanisms in $LaNi_5$ and hydrogen absorption by nano-structured carbons. Griffith University is also conducting real time measurement of hydrogen storage in these novel materials.
- CSIRO Energy Transformed Flagship activities include:
  - Solar assisted steam reforming of natural gas, coal seam methane;
  - Hydrogen generation from fossil fuel sources and renewable sources, including work on electrolysis;
  - Fuel cell technologies (PEM, SOFC, MCFC);
  - Distribution and storage;
  - Nanomaterials, electrochemistry, solid-state ionics and systems integration.

Austria

- *Early pioneer in fuel cell development.*
- *No specific HFC program, but 50 ongoing hydrogen and fuel cell projects, many in collaboration with EU frameworks.*
- *Key programmes: Austrian Advanced Automotive Applications (A3 Programme), and Energy Systems of Tomorrow.*
- *Focus on hydrogen production from renewable energy sources.*
- *Establishing "centres of excellence" concentrating on PEM, fuel cells with circulating electrolytes and SOFC.*

Overview

Austria is one of Europe's early pioneers of fuel cell development. As early as the 1970s, Professor K. Kordesch of the University of Graz constructed a vehicle equipped with an alkaline fuel cell supplied with pressurised hydrogen. Austrian HFC work has primarily been "horizontal" across a number of broad R&D activities.

During the 1990s, Austrian R&D activities concentrated on the following areas: Alkaline fuel cell R&D; basic R&D on DMFC; demonstration exercises of 200 kW PAFC ONSI power plants; and material developments of low- and high-temperature fuel cell systems. This work was mainly driven by industrial developments and yielded achievements such as a stationary hydrogen engine-based CHP plant for industrial applications, and the development of hydrogen storage materials (MeH) and liquid storage tank systems. More recently, R&D activities involving AFC and PAFC have been discontinued, shifting now to work on PEM, DMFC, SOFC (and MCFC) systems.

Despite of having no specific HFC program, 50 ongoing hydrogen and fuel cell projects are being conducted in Austria. In total, up to 40 Austrian organisations are carrying-out hydrogen and fuel cell R&D activities. The Austrian R&D is mainly driven by third party funds: (1) from the Austrian R&D public and/or private funds, and (2) from EU framework program budgets. In total, it is estimated that €7.5 million in 2003 and €7.5 million in 2004 will be spent in the hydrogen and fuel cell fields. Some 20 EU R&D framework programs are central to Austria's ongoing and future activities.

Priorities and targets

In 2001/2002 a fuel cell strategy both for stationary and mobile/portable applications was formulated. The key recommendations of this strategy were:

For stationary/portable applications:

- Participation in International programs like the IEA Implementing Agreement on Advanced Fuel Cells;

- Increased supportive activities for the participation of Austrian R&D entities in EU-Programmes (like the RTD Framework Programmes);
- Initiation of world-class competitive Austrian R&D activities by increased usage of Austrian existing R&D instruments;
- Creation of an Austrian Fuel Cell Cluster fostering public/private R&D activities/initiatives.

For mobile applications:

- Taking advantage of Austria's excellent position in mechanical engineering through the development of suitable balance-of-plant components and adequate production technologies;
- Further improvement of the strong position in the field of electromotive drive units;
- Establishing "centres of excellence" concentrating on PEM, fuel cells with circulating electrolytes and SOFC;
- Research on APUs;
- Development of novel vehicles architectures and concepts.

The Federal Ministry of Transportation, Innovation and Technology (BMVIT) has implemented strategy elements in two new R&D program lines: (1) Austrian Advanced Automotive Applications (A3 Programme), and (2) Energy Systems of Tomorrow. Concerning hydrogen as energy carrier Austria is currently in the process of developing a new strategy, most likely to be finished by 2004.

Concerning hydrogen pathways, Austrian research institutions mainly focus on hydrogen production from renewable energy sources (from biogas, biomass and PV/electrolysis). Extensive modelling activities concerning the prospects for a hydrogen economy (including fuel cells) in future energy systems are carried out by the International Institute for Applied Systems Analysis (IIASA).

In spring 2004 the Federal Ministry of Transportation, Innovation and Technology (BMVIT) established a hydrogen task force within the ministry with the goal to foster the hydrogen/fuel cell topic within the Austrian RTD landscape. It is expected that in 2005, a joint call between A3 and EdZ programs will further strengthen the Austrian RTD activities.

Program activities

- Key areas of Austrian R&D activities may be summarised as follows:
  - Reformer/component development of fuel cell systems fuelled by RES (mainly biogas, solid biomass, and PV);
  - Demonstration projects deploying residential fuel cell systems (PEFC and SOFC);
  - R&D activities for liquid hydrogen storage systems and storage hydride materials;
  - Hydrogen gas engines already deployed in stationary industrial applications;
  - New private/public start-ups of DMFC research activities for portable and mobile applications;
  - APU (PEFC, SOFC) and transportation applications;
  - Concerning standards, Austria developed in 2002 a pre-standard for fuel cell residential CHP systems with a heat load of up to 70 kW.

Budget

Austria presently uses a mix of different public/private R&D instruments to support HFC activities. In total, up to 50 ongoing/future activities were identified by the Austrian Energy Agency analysis: *Hydrogen and Fuel Cell R&D in Austria: Country Picture*, September 2003, which involved more than 40 Austrian institutions and companies. For 2003 and 2004 the total R&D budget for these R&D fields are estimated to €7.5 million each year, respectively.

Key players

- Federal Ministry of Transportation, Innovation and Technology (BMVIT).
- Institute for Chemical Technology of the Technical University of Graz (hosting also the CD Laboratory for Fuel Cells). Here, development of advanced fuel cell electrodes is in progress. This Institute also makes and assembles fuel cell stacks and accessory equipment. Five prototype Apollo™ Fuel Cell have been produced.
- ECHEM – the Austrian electrochemical competence centre in Wiener Neustadt, is also active in advanced electrode developments (including catalyst research) but also in high power, short stack manufacturing and testing.
- Plansee AG is developing chrome-based alloys for SOFC fuel cell bipolar plates deployed in residential applications.

Other Activities

- GE Jenbacher is producing gas engines for stationary applications using process gases with high hydrogen content for industrial applications in a power range between 100 kW and several MW. The engines achieve electrical efficiencies up to 40% (LHV) and total efficiencies up to 90% (LHV). The LEANOX patent guarantees NOx emissions from these engines as low as 5 parts per million (ppm).
- Magna Steyr is developing innovative and cost competitive liquid storage tanks. The research activities concentrate in the short term to high pressure vessels and cryogen storage vessels and in the medium to long term to novel solid storage materials.
- Treibacher Industrie is developing metal hydrides with a view to improving and optimising their H_2 storage properties for effective use in stationary and mobile energy systems.
- The Apollo™ Fuel Cell work has made considerable progress, including new electrodes which develop over 100% more power than the previous ones. In addition, a new ammonia-based "Propulsion Fuel" has been developed together with an ammonia cracker. This propulsion fuel is fed into the cracker, which then breaks down the ammonia (NH_3) into hydrogen for the fuel cell and harmless nitrogen (normal air contains approximately 78% nitrogen and 21% oxygen). As the major work in the fuel cell program at TU Graz has been completed and patent applications on the new electrodes, propulsion fuel and the ammonia cracker have been filed, the company is now transferring the fuel cell program and some of the technical personnel to Fort Lauderdale, Florida, USA. Prototypes will be made at new Tech Centre for use in electric vehicles and in Apollo™ Power Plants for supplying on-site power to homes independent of the electric power grid.

- The Austrian gas utility companies Energie AG Oberösterreich, Wienstrom, ESTAG and SAFE are testing PEM and SOFC residential fuel cell power plants from Sulzer Hexis and Vaillant companies.
- IIASA – the International Institute for Applied Systems Analysis is carrying-out extensive modelling efforts of a future hydrogen economy (incl. fuel cells).

Belgium

- *Active participant in a number of EU framework projects.*
- *Strong involvement by regional governments.*
- *Demonstrated experience with hydrogen transmission grids.*
- *HFC focus on renewable energy and decentralised cogeneration.*

Overview

Although there is no specific national R&D program, Belgium in working on a number of individual projects to explore the potential of hydrogen and fuel cells, including a seven individual field projects on fuel cells.

The Walloon region is particularly active in supporting a number of projects on hydrogen, fuel cells and related technologies. Belgium is also a participant in several of the EU-sponsorded HFC programmes. Notably, Belgium has practical experience in the area of hydrogen transport and distribution and is central to the Air Liquide Industries hydrogen grid that connects chemical industries and oil refineries throughout Belgium, France and the Netherlands.

Priorities and Targets

The most recent Belgian coalition agreement stated: "Research and development of renewable energy, decentralised cogeneration, fuel cell technology and energy-efficient technologies, will be supported, in cooperation with the regions." Two policy studies are under way: (1) the development of tools to evaluate the potential for sustainable hydrogen in Belgium; and (2) an initiative on the future role of HFC systems in Flanders through 2050.

Program activities

- ProCoCo: Miniaturisation and integration of a hydrogen generator with a fuel cell.
- HYDROGEN: Hydrogen generation from natural gas and alcohols.
- GAZOPILE: Study on fuel cell feeding from a wood gas generator.
- BIO-H_2-FC, Biological production of hydrogen for fuel cell from organic residues.
- SYNATEC: synthesis of multi-wall and single-wall carbon nanotubes.
- Carbon Sequestration: Study on the potential of CO_2 storage in the "Kempen"'-Flanders; a study on the influence of super critical CO_2 on reservoir rocks; and participation to the European project RECOPOL for the enhanced coal bed methane extraction.
- NANOCELL: Nanocompounds application to design of fuel cell membranes.
- Establishment of a fuel cell laboratory for PEM.

- Methylal: Research project on direct methylal fuel cell.
- Sart Tilman Project: Establishment of Ballard stationary fuel cell, PEM of 220 kW.
- The Green Family: Mini fuel cell for combined energy production in domestic use.
- Accept: PEM stack fuelled by ammonia (via a reformer) for automotive use.
- ELEDRIVE: participation in the thematic European network on fuel cells and their applications for electric & hybrid vehicles.
- Mini-UAV: Design of a Mini-UAV (Unmanned Aerial Vehicle) using a Fuel Cell Propulsion System.
- Development of a knowledge centre on FC technology.

Budget

Belgium has allocated roughly €3.4 million and €4.2 million for RD&D on hydrogen and fuel cell work, respectively.

Key players

- Research on fuel cells systems is done by the university of Liège and by Flemish Institute for Technological Research (Vito, Mol).
- Promocell: field projects with fuel cells and is involved in research projects in Wallonia.
- Air Liquide Industries: hydrogen grid.
- Vandenborre Hydrogen Systems: electrolysers (acquired by Stuart last year).

Key players on fuel cells:

- Solvay: membranes.
- E-Vision: alkaline fuel cells.
- Bekaert: fuel cell components.
- Umicore: fuel cell components and catalysts (via DMG).
- Microtherm: fuel cell components.

The Belgian Fuel Cells Industry

A collaboration between industrial players and research organisations was set up to enhance the innovative research on fuel cells within the Flemish region. This partnership is financed with public and private funds and started in June 2003 with 12 companies.

Other Activities

- In October 2003, Fuel Cell Technologies (FCT) Ltd. (Canada) announced that it had signed a contract to manufacture and supply one of its Second Generation Series SOFC 5 kW units to the University of Liège in Belgium. As of October, 2003, FCT's First Generation Series of 5 kW SOFC units had generated a total of over 34 MW-hours of electricity.

Canada

- ***Short-term commercialisation, industry-focused program.***
- ***Key technology developments: Ballard PEM fuel cells and Stuart Energy electrolyzers.***
- ***World's first fuel cell bus demonstrations.***
- ***Hydrogen infrastructure development through the Canadian Transportation Fuel Cell Alliance.***
- ***Early market introduction of hydrogen and fuel cell technology through the Early Adopters Program.***
- ***Annual government investment on research and development is approximately C$20 million.***
- ***Canadian manufacturers are among the world leaders in HFC R&D, manufacturing, demonstration and commercialisation.***

Overview

Canada has a longstanding involvement in the development of hydrogen and fuel cell technologies, with government investment of some C$200 million since the early 1980s. The hydrogen R&D program has been managed by Natural Recourses Canada (NRCan) since 1985, through cost-shared agreements with the private sector. Two of the most successful technologies supported during the late 1980s were the Ballard PEM fuel cell and the Electrolyser Corp (now Stuart Energy) alkaline water electrolyser. These early efforts let to the demonstration in 1993 of the world's first fuel cell bus; R&D efforts continued and in 1996, a second generation bus was demonstrated. With the success of these first fuel cell buses, a fleet demonstration was launched in 1997 which integrated numerous hydrogen technologies and illustrated they could function as a whole system including hydrogen production, storage and utilization in a fuel cell.

Canada's Hydrogen and Fuel Cell R&D Program is managed by the partnership between NRCan's CANMET Energy Technology Centre with other federal government departments, including the National Research Council and the Department of National Defence.

Until recently, the Canadian HFC programme was largely focused on research and development. With the demonstrated success of key hydrogen production and fuel cell technologies, the scope of the program was broadened substantially to include several additional federal departments and programmes, including Industry Canada's commercialisation efforts, which illustrate the success of past R&D programs and demonstrates the industry is maturing to a point where it can play an active role in market development.

Priorities and Targets

The vision of the national program is to strengthen and enhance Canada's leadership position in the supply and demand for renewable and sustainable energy from fuel cells and hydrogen with the ultimate goal of accelerating the commercialisation of Canadian fuel cell and hydrogen products for Canada and the world. Canada's program targets are delineated in 3 phases, concentrating on RD&D and early deployments in the first five years; broad-based deployment in the period 5 to 10 years out; and market expansion in the longer-term.

Program activities

Canada's national program consists of three areas: research and development; hydrogen infrastructure development through the Canadian Transportation Fuel Cell Alliance; and early market introduction of hydrogen and fuel cell technology through the Early Adopters Program.

- **The Hydrogen and Fuel Cell R&D programs.** encourages innovation by facilitating R&D partnerships through cost-shared agreements with the private sector, frequently under multiple partner arrangements. The program is focused on the development and evaluation of hydrogen systems and fuel cell technologies for transportation and stationary power, including off-grid applications. Program activities are oriented toward the development of technologies with short-to-medium term commercial potential. The R&D program focuses on hydrogen production and storage; novel materials and architectures; fuel cell commercialisation; and the development of coordinated hydrogen and fuel cell standards that will be required for hydrogen to be a safe and cost-effective energy carrier. The program is managed by Natural Resources Canada; National Research Council, Natural Sciences and Engineering Research Council, Department of National Defence and Environment Canada. The annual budget is approximately C$20 M/year.
- **Canadian Transportation Fuel Cell Alliance.** The Canadian Transportation Fuel Cell Alliance is one of the initiatives of the Government of Canada's Action Plan 2000 on Climate Change. Its primary focus is to demonstrate and evaluate fuelling options for fuel cell vehicles in Canada. Different combinations of fuels and fuelling systems are to be demonstrated by 2005, for light, medium and heavy duty vehicles. The initiative will also develop standards and training and testing procedures as related to fuel cell and hydrogen technologies. The seven year budget allocation is C$33 million – not including partners. To implement this initiative, NRCan established a Core Committee, a Project Advisory Committee and five Working Groups. The effective functioning of these groups relies heavily on the efforts of about 100 individuals representing Canadian hydrogen and fuel cell companies, industry associations, municipalities, non-government organisations, gas and electric utilities, universities and colleges, provincial governments, and several federal government departments and agencies.
- **The Early Adopters program** is led by Industry Canada and seeks to work in partnership with industry stakeholders to foster the development and early adoption of hydrogen technologies. It will enable firms to showcase their technologies in pilot-scale versions of a hydrogen economy and will help increase investor and consumer awareness of Canadian capabilities and of the many benefits and uses of hydrogen-powered applications. Working together, Government and industry will foster the development and early introduction in the Canadian marketplace of hydrogen and hydrogen-compatible technologies, such as fuel cells and those used to produce, store and distribute hydrogen. The H2EA program will lead efforts to demonstrate new concepts, such as "hydrogen highways" and "hydrogen villages". The five year budget is C$50 million.

Other significant projects underway

- **Fuel Cell Commercialisation Roadmap.** The development of the Fuel Cell Commercialisation Roadmap was an industry-led planning process supported by the government of Canada. Its objective is to accelerate full-scale commercialisation of fuel cell technologies by Canadian fuel cell companies. It represents a critical step in identifying the commercialisation challenges and in selecting the strategies and actions that will allow Canadian stakeholders to successfully meet these challenges. The Roadmap is now published and a work-plan has been drafted to begin implementing the report's recommendations.
- **Hybrid Fuel Cell Transit Bus.** This hybrid bus development project is a joint initiative that will use a bus built by New Flyer powered by a Hydrogenics fuel cell, and utilizing Dynetek hydrogen storage cylinders, Maxwell Technologies ultra-capacitors and ISE Research control technologies for energy management and systems integration. The use of ultra-capacitors is expected to improve efficiency by as much as 25% over a fuel cell only bus. The bus is to be demonstrated in Winnipeg, Manitoba in 2004.
- **Fuel Cell Vehicle Demonstration.** This project will demonstrate the third generation Ford fuel cell Focus. Five vehicles will operate in Vancouver, beginning in 2004. The project is managed by Fuel Cells Canada and funded by Natural Resources Canada, the government of British Columbia and the National Research Council. Results of the demonstration project will be used to influence future technology development. The budget is C$5.8 million over three years.
- **IMW Industries Hydrogen Compressor and Dispenser System.** IMW Industries is developing a high-pressure hydrogen compressor and dispenser system for small-scale (30 vehicles and two buses per day) and large-scale (300 vehicles and 20 buses per day) hydrogen fuelling stations. This hydrogen compressor system is intended to ensure full fill at 350 and 700 bar.
- **Hydrogenics Fuel Cell Power Module.** Hydrogenics Corporation is developing a 10 kW fuel cell power module for use in off-road vehicles and power generation applications. This design will demonstrate higher efficiency, lower cost, smaller size and improved manufacturability over previous designs.
- **H_2 Roadmap.** Currently under development in Canada and led by NRCan, the Roadmap will consider the role of hydrogen, fuel cells and related technologies may play in the short, medium and long term in Canada's energy economy and in addressing environmental challenges. The process will seek to build consensus between industry, government and other stakeholders on the ways to encourage the strategic development and use of hydrogen in Canada. The Roadmap will produce a vision and mission for the hydrogen economy in Canada that identifies opportunities and barriers to achieving goals and a detailed action plan that defines industry and government actions needed to address barriers and promote identified technologies.

Budget

The government of Canada has invested over C$200 million in the hydrogen and fuel cell sector since the early 1980s. This amount includes only federal funding and does not include funds spent by provincial governments nor does it include private sector investment.

Yearly spending on research and development is approximately C$20 million (C$10 million per year from Natural Resources Canada and C$10 million per year from the National Research Council).

Additional support of approximately C$13 million is also provided to the hydrogen and fuel cell industry through other innovation and climate change programs.

The federal government has recently (October 2003) announced a further C$215 million to set the groundwork for developing a hydrogen economy in Canada. The investment is directed (as discussed above) at: (1) early adoption of hydrogen technologies through integrated demonstration projects undertaken by partnerships; (2) improved performance and reduced costs of hydrogen technologies; and, (3) initiatives to establish a hydrogen infrastructure through Sustainable Development Technology Canada.

Key players

- National Research Council (NRC)/Institute for Fuel Cell Innovation. The NRC's hydrogen and fuel cell program is led by the Institute for Fuel Cell Innovation (IFCI) in Vancouver but is linked to NRC Institutes across the country to maximise leverage of research expertise and facilities. The program also includes the Natural Sciences and Engineering Research Council/NRC Research Partnership Program that has funded projects in conjunction with industry and universities. The Incubator/Industrial Partnership Facility was established in December 2001 as part of NRC's national community technology cluster strategy to help support the development of a British Columbia fuel cell technology cluster. It contains incubator and hydrogen safe lab space, and is located at NRC Institute for Fuel Cell Innovation in Vancouver. It currently has nine hydrogen safe labs, a large scale environmental chamber, and 5 tenants, typically start-up companies doing collaborative research with NRC.
- Industry Canada supports the development of new energy technologies including fuel cells and hydrogen. Its activities include demonstrating pilot and large scale technology projects through its programs like Hydrogen Early Adopters; increasing access to investment capital for emerging companies, and addressing technical barriers to distributed generation. Industry Canada also develops a wide range of polices and programs to enhance the economic climate for growth of the Canadian hydrogen and fuel cell industry.
- Natural Resources Canada, CANMET Energy Technology Centre.

The Canadian fuel cells industry

A key factor in the past successes of the Canadian program was the variety of superior domestic hydrogen and fuel cell technologies under development in the private sector. This has led to the development of a number of innovation clusters (one very notable one in Vancouver) where there is a critical mass of talented people and technologies available which have spurred ongoing development. Canadian manufacturers are some of the world leaders in hydrogen and fuel cell technology R&D, manufacturing, demonstration and commercialisation, including: Ballard Power Systems, Dynetek Industries Ltd, Fuel Cell Technologies, and Stuart Energy Systems, and the Hydrogenics Corporation.

Denmark

- ***National research strategy aimed at SOFC and PEM fuel cell development.***
- ***Annual government investment in fuel cell R&D projects is approximately €18 million.***
- ***Participation in a 13 different EU-sponsored fuel cell projects.***
- ***Key industry cooperation and support from Elkraft and Eltra.***

Overview

Denmark has a strong, consolidated R&D community engaged in national, Nordic and European R&D activities related to hydrogen and fuel cells. Energy research on hydrogen and fuel cells has in the last five years been supported by the National Energy Research Program (EFP), the Public Service Obligation Funds for R&D within environment and electricity (PSO), the Research Councils, and the short-lived Hydrogen Program (1999-2001).

The National Energy Research Program has historically supported R&D projects on SOFC, while the Hydrogen Program has supported both hydrogen and fuel cell R&D activities. A total of 34 projects with a budget of €22 million have been approved in the period from 1998 to 2002 – some of which have been completed while others are still running. Of this mix, the Hydrogen Program was launched in 1999 in order to give priority to pre-competitive research and demonstration projects in hydrogen technologies and development and application of PEM fuel cells for both stationary and mobile applications. Some 14 projects with a total budget of €4.8 million have received support from the program.

Based on these past R&D activities, a national research strategy has recently been made for fuel cells covering both SOFC and PEM. A national RD&D strategy for hydrogen technologies is under preparation by the funding agencies in close cooperation with key stakeholders from industry, academia and the energy companies. The strategy will be finalised in the first part of 2005.

Priorities and targets

In 2003 the Danish Energy Agency, Elkraft and Eltra published strategies for four priority fields for Danish energy research: (1) wind energy; (2) biomass; (3) photovoltaic; (4) fuel cells. The Danish national research strategy for developing fuel cells concentrates on SOFC and PEM technologies and includes the following objectives:

- To maintain and develop Danish R&D at high international levels;
- To involve Danish industry in this development;
- To assure internationally competitive Danish products in terms of price, durability, environmental and technical feasibilities;

- To bring the products to the market;
- To orient R&D on fuel cells towards possible applications in Denmark and elsewhere;
- To educate researchers, technicians, engineers in the field;
- To maintain and build Danish know-how, e.g. through active patenting.

Selected project activities

- **The PSO-Eltra project** is a Pre-pilot SOFC production plant designed to scale-up existing laboratory production methods, build the necessary know-how for establishing industrial production, improve reproduction possibilities and develop non-destructive methods for production control. The project ran from 2001-2003, participants included Risø, Haldor Topsøe, and Eltra.
- **The PSO-Elkraft Project** established fuel cell testing facilities for the Danish-developed Solid Oxide Fuel Cells (DK-SOFC). Some lifetime factors have been identified and a new generation of cells have been developed with improved lifetime performance.
- **The CORE-SOFC Project** was designed to improve the durability of planar SOFC systems to a level acceptable for commercial operation. The work focuses mainly on materials selection for interconnects, contact layers and protective coatings to minimise corrosion between metallic and ceramic parts to achieve reliable and thermally-cyclable SOFCs. In all work packages, cells and stacks will be analysed by advanced chemical and ceramographic methods.
- **The MF-SOFC Project:** Scale up of a multi-functional solid oxide fuel cell to multi-tens of kilowatt levels. This program aims to develop a new generation of affordable indigenous European Multi-Functional Solid Oxide Fuel Cells (MF-SOFCs), built from a universal MF-SOFC module fabricated by cheap processes. It serves both sub-MW standalone combined heat and power, and multi-MW combined SOFC/gas turbine cycle systems. Scale up is proposed both in rating and production volume. The project comprises a vertically integrated team from: Rolls-Royce, Risø National Laboratory, Imperial College, Advanced Ceramics Limited, and Gaz de France.
- **The EFP Project:** Long-term SOFC development. The purpose of the Danish fuel cell program is to develop a technology for energy efficient and environmentally-friendly electricity production. Based on the results achieved by the Danish SOFC program, together with the interest shown by Danish industry, a strategy has been developed for the commercialisation of SOFC technology. The Danish SOFC project is structured in two parts. The first part is aimed at solving the short-term problems that occur in the experimental development and demonstrations of Danish fuel cell and stack technology. The second part of the project is a five-year plan aimed at establishing a long-term development path, leading to the reduction of the operating temperature of a fuel cell, without increasing area specific resistance. Furthermore, the project aims to improve the robustness of cells, material structures and components, and partly to understand the operational relevant mechanisms. An important part of the project is to build up know how by establishing patents, which can secure a leading position for future industrial co-operation. The projects industrial partners are IRD A/S and Haldor Topsøe A/S. Academic partners are the Chemical Institute, Odense University and the Institute for Chemistry at the Danish Technical University.
- **The Hydrogen Project:** A vehicle based on a Danish-produced PEM fuel cell made by IRD fuel Cells A/S. The objectives of the project are to finalise the construction and to demonstrate

the fuel cell driven electrical hybrid car. The car is intended for demonstrating hydrogen as a fuel in the transport sector. The hybrid car functions as a laboratory where components and modules in the future can be upgraded with improved versions. Two hybrid cars are being manufactured, one for Fiat and one for IRD and tested in the laboratory and demonstrated on a test track. Other partners are Centro Ricerche Fiat (IT) and the Folkecenter for Renewable Energy (DK).

- **The EU Project: High temperature PEMFC Stack with Methanol Reforming** aims at developing an integrated Advanced Methanol Fuel Cell system, based on a cost-efficient polymer membranes operating at about 200°C. The fuel cell will be thermally and physically integrated with a methanol reformer and a catalytic burner. The increased operating temperature of the fuel cell will make it possible to design a fuel cell system with improved efficiency, simultaneously reducing cost, size and complexity of the complete power system. Project partners are Volvo/S), Technical University of Denmark, Statoil (N), NTNU (N), University of Newscastle-Upon-Tyne (UK), and Proton Motor Fuel Cell (D).
- **Towards a hydrogen-based society** is a centre of excellence on catalysis, storage and demonstration of small energy units and is supported by the Research Council (€3 million). The centre is made up by key university and industrial research communities and has a strong focus on fundamental research while at the same time establishing collaboration between basic and applied science communities including Danish industry.

Budget

Total budget for realising the strategy comes from various public support schemes:

- The National Technical and Natural Science Research Council (€20 million).
- National Energy Research Program (€23 million annually).
- Public Service Obligation Funds (€13.5 million annually).
- The annual investment in 2003 in fuel cell R&D projects is approximately €18 million, with €11 million allocated to SOFC and €7 million to PEM fuel cells. This represents a significant increase in fuel cell R&D fuel cells compared to the previous 20 Danish projects launched between 1998 and 2002, with a total budget of €14.50 million.

Venture capital also plays a role in Denmark. The Danish manufacturing company Danfoss A/S has recently joined the Conduit Ventures Limited, the first European based venture capital company, which focuses purely upon fuel cells and related hydrogen technologies. Danfoss A/S has added US$5 million to the fund.

EU programs

Danish research communities are well represented in European research and demonstration projects in the area of fuel cells. In the period 1999-2002, 43 projects were supported by the EU's Fifth Framework program on Energy Environment and Sustainable Development (EESP). Overall, Danish partners have participated in EU-sponsored 13 fuel cell projects *(For more information see the Nordic programmes)*.

Nordic energy research

Nordic Energy Research Programme is a Nordic institution under the Nordic Council of Ministers and is funded by the Nordic Governments. In the area of hydrogen and consequences of climate changes for the energy sector, €2.3 million have been allocated to 6 hydrogen energy projects. Danish partners participate in all projects *(For more information see the Nordic programmes)*.

Key players

Major public and private organizations involved in fuel cell R&D projects include:

- Risø National Laboratory (*www.risoe.dk*)
- Technical University of Denmark, the Interdisciplinary Research Centre for Catalysis (*www.icat.dtu.dk*)
- Haldor Topsøe A/S (*www.topsoe.dk*)
- Technical University of Denmark, Chemical Institute (*www.materiale.kemi.dtu.dk*)
- IRD Fuel Cells A/S (*www.ird.dk*)
- Danfoss A/S (*www.danfoss.dk*)
- University of Southern Denmark (*www.sdu.dk/indexE.html*)
- University of Aalborg, Institute of Energy Technology (*www.iet.aau.dk/*)
- University of Aarhus, Interdisciplinary Nanotechnology Centre (*www.inano.dk*)
- Danish Gas Technology Centre A/S (*www.dgc.dk*)
- Danish Technological Institute (*www.danishtechnology.dk*)
- Folkecenter for Renewable Energy (*www.folkecenter.dk/en/*)

Finland

- ***Focus on distributed hydrogen-related energy systems.***
- ***R&D work on PEM, AFC, DMFC and SOFC.***
- ***Significant participation in international programs and networks, including EU, Nordic and IEA.***

Overview

Primarily through the National Technology Agency (Tekes), Finland has been investing in Fuel Cell and Hydrogen R&D since 1995.

Priorities and targets

The hydrogen strategy is to focus on distributed hydrogen related energy systems, network with international activities (EU, IEA, Nordic), and connect with fuel cell activities in Finland. Finland's fuel cell strategy is a bit more developed, with plans to focus on systems, fuel cell demonstrations and applications, build a close relationship with industry to create a national fuel cell group, and network with international fuel cell initiatives.

Program activities

- **Low temperature Fuel Cells (PEM, AFC, DMFC).** The aim of the project is to improve the overall performance of low temperature fuel cell technologies studied in Finland. The technologies included are alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEM) and methanol fuelled enzyme-catalysed fuel cells (i.e. biofuelcell). The main target of the research during 2003 was to demonstrate and verify the performance of fuel cell technologies in different applications. The AFC has successively been integrated and tested in a boat (200 W) and one was tested in a small-scale electric vehicle application (1 kW). A free convection PEM fuel cell (10-100 W) for a portable computer application is under design and construction, and a PEM module for microCHP (combined heat and power) is under construction (1.5 kW). The first BIO prototype is completed and will be demonstrated as a power unit in a mobile phone application. Participating companies: Alkomohr Biotech Ltd, EL-3 Ltd, Finnish Chemicals, Gasum, Oy Hydrocell Ltd, Labgas, NAPS Systems, Prizztech, Woikoski and Wärtsilä. Research Partners: Laboratories of Automation technology (Aut), Advanced energy systems (Ene), Physical Chemistry and electrochemistry (Fyke), Materials processing and powder metallurgy (MVT), Applied thermodynamics (Sote) and Industrial Chemistry (Tek) from Helsinki University of Technology. The project budget is €1.3 million.
- **FINSOFC 2002-2006 "Business for Finnish companies."** Various elements of the project are to: generate sufficient know-how in selected areas; build a sufficient platform for SOFC related

research and development; build a SOFC-network between companies and research institutes; advance international networking and co-operation, especially within EU; promote SOFC technology and it's business potential; generate new business opportunities for Finnish companies within FC technology. Work concentrates on fuel reforming and SOFC construction & demonstration. VTT Processes, Wärtsilä Oyj, Fortum Oyj, Patria Vehicles Oy, VNT Management, Jyväskylän Energia Oyj, Espoon Sähkö Oyj, Joroisten Energia, Helsingin Energia, Haminan Energia. The project budget in 2003 was €1.12 million; the 5-year budget is estimated at close to €5 million.

- **DENSY (Distributed Energy Systems).** The program is financed by Tekes (National Technology Agency of Finland, *www.tekes.fi/eng/default.asp*), with the goal to grow the export income of Finland. Tekes will invest €21 million in the DENSY program during its five year period and expects enterprises and partners to raise the total sum up to €47 million. In addition to Tekes, Merinova, the Finnish National Fund for Research and Development (SITRA), Finpro and the Ministry of Trade and Industry will take part in the program.

Budget

The Finnish budget for HFC work is divided into fuel cell R&D and hydrogen. For fuel cells, the budget from 1995 through 2002 was €11.5 million. For 2003, it was €4 million. For hydrogen, the budget from 2000-2002 was €0.68 million. For 2003, it was €1.4 million.

Key players

Research organizations

- VTT Processes – hydrogen R&D activities.
- HUT – metal hydrides and hydrogen production.
- University of Jyväskylä – hydrogen production from biogas by fermentation.
- University of Tampere – NEFP project "BioHydrogen."
- Helsinki University of Technology.
- University of Helsinki/Laboratory of Polymer Chemistry.
- Åbo Akademi University.

The Finnish fuel cells industry

- NAPS Systems — Develops PV-hydrogen energy systems.
- Labgas/Reijo Varila — Develops and sell hydrogen generators for laboratories.
- Hydrocell — Develops alkaline fuel cells and metal hydride storages.
- Woikoski — Produced hydrogen gases for industrial use.
- Finnish Chemicals — Produces hydrogen as a by-product in paper chemical manufacturing.

International activities

Finland reported considerable activity in a number of international programmes.

Hydrogen

- IEA Hydrogen implementing agreement:
  - Production (photoelectrolytic, photobiological, hydrocarbons).
  - Storage (solid and liquid state materials).
  - Design and optimization of integrated systems.
- EU/6.WP/Sustainable energy systems.
- Nordic Energy Forskning Program (NEFP):
  - New metal hydrides for hydrogen storage, 0.5 M€, HUT/SoTe.
  - BioHydrogen, 0.8 M€, JU, TUT.
  - Integration of advanced H storage materials and systems into society, 1.2 M€, HUT/Advanced energies.
- Nordic Industrial Fund:
  - Hydrogen energy foresight in the Nordic countries, VTT, ABB, Wärtsilä, Fortum O&G.

Fuel Cells

- Nordic Co-operation (Denmark, Finland, Iceland, Norway, Sweden):
  - Hydrogen production and storage (3 projects).
- European Union:
  - SOFC Network (VTT/Processes, Wärtsilä).
  - Fuel Cell Testnet (VTT/Processes).
- OECD/IEA/Advanced Fuel Cell Implementing Agreement:
  - Stationary applications development (VTT/Processes).
  - SOFC development (VTT/Processes).
  - Preparing PEM (HUT/Automation).

France

- *Fuel Cell Technological Research Network (PACo network) to foster creativity and innovation needed for the commercial development of fuel cells.*
- *Strong participation by French research organisations and energy agencies, CEA, CNRS, ADEME.*
- *Fuel cell activities concentrated on PEM and SOFC.*
- *Work on massive hydrogen production using innovative high temperature processes.*
- *Annual government investment of approximately €40 million.*

Overview

Research on fuel cells started in France in the early 1960s, mainly conducted by the major players in the energy sector before it was abandoned in the late 1970s. Some research organisations, such as the CEA (Atomic Energy Commission), continued limited development of PEM technology and in 1987 restarted research work by adapting PEM technology to fuel cells. In 1989, the car manufacturer PSA prepared a working document for a development program including hydrogen and fuel cells and was later joined by Renault. In 1990, the French government launched the national Clean Energy Vehicle program, which included technologies of the future such as hydrogen and fuel cells. Subsequently, French research agencies CEA and CNRS have joined HFC work as collaborators. The work was extended to other partners during 1995 to 2000 via the European Hydro-Gen project, demonstrating a fuel cell vehicle with hydrogen stored on board in a high pressure tank. Along with the French company Ullit, the CEA developed the first 700 bar composite hydrogen storage tank.

In 1999, the Ministry of Research, in association with the Ministry of Industry, created the Fuel Cell Technological Research Network (PACo network) to contribute to French energy policy for the development of new energy sources. The purposes of the network were to foster creativity and innovation needed for the commercial development of fuel cells and to encourage public-private partnerships and facilitate interdisciplinary cooperation. In July 2000, the government launched CNRT (Centre National de Recherche Technologique) in Belfort-Montbéliard, involving the construction of a fuel cell test platform dedicated to transport applications. The fuel cell test capacities have demonstrated power up to 200 kW.

Fuel cell activities are concentrated in two main areas: PEM (including DMFC technology) and SOFC technologies. The main financing bodies are (with decreasing order of involvement): the PACo network, ADEME, PREDIT, ANVAR, the DGA, and French regions (via Regional Councils), departments (via Departmental Councils) and districts.

Work on production, storage and transportation of hydrogen as an energy carrier was carried out in France as early as 1975, by the DGRST under the Energy R&D European program. Hydrogen production via high temperature processes is conducted by a variety of organisations, including

Uranium Pechiney, Ugine Kulhmann, Citroën, EDF, GDF, Laboratoires de Marcoussis, SRTI/Creusot-Loire, CEA, IFP.

In 1986, the Association Lorraine pour la Promotion de l'Hydrogène et de ses Applications (ALPHEA) was created in Forbach to evaluate the energy potential of hydrogen. In 1998, the Association Française de l'Hydrogène (AFH_2) was founded, bringing together all French players in this field. The hydrogen R&D activity started again in 2001 after CEA decided to support the development of high temperature gas-cooled nuclear reactors, which cover a wide variety of high temperature applications. Concurrently, the CNRS launched the program "Energy" with different themes on hydrogen.

Numerous public organisations participate in the finance, research and development of hydrogen and fuel cells in France, using their own resources or resources either from industry or from EU programs, in particular the EU FP5 programs (see more information on EU program). Furthermore, France has conducted important work on hydrogen for space applications in the framework of the ARIANE launchers program.

Program activities

- **PEMFC:** R&D areas include slightly higher temperature (120°C) and lower cost membrane materials, resistant and low-cost catalyst materials, long life. The technology must meet all the basic criteria for performance, durability and cost. Examples of projects include:
  - Ecopac project: polymer membranes prepared by extrusion;
  - New membranes for alkaline fuel cells (Alcapac project for microfuel cell, Palcam project);
  - Alternative polymer membranes for higher temperature applications (sulfonated polyimide blends), degradation studies;
  - Development of CO resistant catalysts;
  - Micromet project: manufacturing of MEMS fuel cells with high power density;
  - Pactol direct project: development of catalysts working with ethanol at low temperature;
- **SOFC:** R&D areas include stack material and architecture combinations that allow effective sealing and reduction in life-limiting thermal stresses, material combinations allowing high power densities at moderate temperature, long life and reduced costs, architecture and materials that can realistically implement internal reforming. Examples of projects include:
  - SOFC-RIP project: SOFC stack with internal reforming;
  - SOFC-BT project: development of materials for operation at 600-800°C;
  - APUROUTE: Study of an APU SOFC for transport applications.
- **Hydrogen production through synthesis gas generation:** Air Liquide and Technip are active in this area, working on different stages of synthesis gas production, hydrogen/CO_2 separation and hydrogen purification, as well as developing new options for producing hydrogen with CO_2 sequestration. Alstom and IFP are involved in different studies concerning clean power generation through hydrogen production from coal or natural gas and participate in the EU FP6 ENCAP project.
- **High temperature processes:** CEA, CNRS and industrial companies such as EDF and Framatome are carrying out R&D programs on massive hydrogen production using innovative high temperature processes. One part of this program (CEA) is a joint program with US DOE under

the GEN IV Umbrella, with Sandia and General Atomic to working together on feasibility and developing a thermochemical cycle in order to produce clean hydrogen and heat from future HTR nuclear plants. CEA is carrying out some experimental work on thermodynamics, kinetics, and materials to characterize the chemical reactions and to determine the key points and the breakthroughs needed. The CNRS has facilities that study high temperature concentrated solar applications and possible hydrogen production from these means.

- **Low or room temperature processes:** R&D on photobiological processes is carried out by CEA and CNRS in cooperation with European programs. French teams have been funded by the EU for artificial and natural photosynthesis within research networks involving other leading European groups: the Ru-Mn chemistry for Artificial Photosynthesis for fuel production (1996-2000) was coordinated with the Swedish Consortium for Artificial Photosynthesis. With the EU 6th framework, new networks are being formed. The Swedish Consortium and the French groups are working together with leading European groups from Germany, Greece, Hungary and the Netherlands to form a new network called "Solar-H: hydrogen from sun and water – a blue skies research project for a greener planet".
- **Small reformers:** R&D areas include compact and low cost reformers (1-5 kW) to convert fossil fuels (natural gas, gasoline) or biomass fuels (ethanol) to hydrogen via different processes (steam reforming, partial oxidation, auto-thermal, non catalytic hybrid steam reforming). Improvements in reformer efficiency, capacities and response times, and integration of purification unit are also being studied. Examples of projects include:
    - Opale project: reforming of fuels by POX;
    - Refopem project: reforming of natural gas by autothermal process in coupling with PEM;
    - Saparef projects: on-board reforming for automobile applications (APU coupled to PEM);
    - Biostar project: reforming ethanol with integrated purification metallic membrane.
- With respect to hydrogen storage, R&D is oriented to the development of lightweight, low cost, and low volume hydrogen devices (storage capacity target > 6.5 wt%). Examples of projects include:
    - Physe project: development of a new plastic-lined and carbon over-wrapped tanks (water volume of 3 litres and storage pressure of 300 bars);
    - Polystock project: development of plastic lined composite tank (higher volume, development of materials for pressure of 700 bar), study of fast filling procedures;
    - Cash project: hydrogen storage in activated carbons.

Budget

The total amount of funding provided by public entities in 2002 was estimated at €40 million. This figure includes all subsidies provided in France by the European Union for "hydrogen and fuel cells" work as part of the FP5 program. French public authorities have expressed the desire to develop HFC technologies more extensively, and the French Prime Minister confirmed the "Clean vehicles" plan, which should lead to additional support of €40 million over a period of 5 years.

Key players

- **The PACo network:** This network was created in June 1999 to encourage the combining of public research and industrial research in the fuel cell field and to support funding of selected R&D projects. The PACo network is guided by a high level Steering Committee which comprises leading representatives from companies, government, universities and research institutes to identify appropriate routes for fuel cell development. Several governmental agencies provide funding to these R&D projects (Ministries of Research, Industry and Transport, ADEME, ANVAR). Although focused on fuel cells, the network also deals with the question of the fuel via the development of small reformers for hydrogen production and the development of hydrogen storage technologies.
- **CNRS:** Of the numerous structures of the CNRS, three concern hydrogen and fuel cells – one program unit and two research groups (GDR) working on fuel cells.
- **CEA (Atomic Energy Agency):** The main lines of the CEA program are the production of hydrogen (thermo chemistry and steam electrolysis combined with future high-temperature nuclear reactors, biomass); storage (high pressure storage and new types of storage for portable applications, carbon nanostructures); PEM type fuel cell (components, systems, and phenomenology); SOFC type fuel cell (components and stack) and studies on the feasibility of a Hydrogen Economy (technology watch, techno-socio-economic studies, safety, etc.).
- **IFP (French Petroleum Institute):** IFP has been active for many years in the area of hydrogen production, transportation, storage and use. Hydrogen is also a key component for the industrial processes developed by IFP.
- **ADEME:** This national agency deals with renewable energies, energy savings and their associated technologies. Fuel cells and hydrogen were included in its sphere of activities in the early 1990s and numerous actions under the PACo network are financed by ADEME.

The French fuel cells industry

The PACo network mainly contributes to the fuel cell activities of the R&D public sector. Although focused on fuel cells, the network also deals with the question of the fuel via the development of small reformers for hydrogen production and the development of hydrogen storage technologies. The main topics are: (1) small reformers supplied with different fuels; (2) materials and components for hydrogen storage (gas storage, hydrides, carbon materials); (3) fuel cell focus on PEM, DMFC and SOFC; (4) systems, tests, demonstrations; and (5) cross topics, including safety, regulations, and techno-economic analyses.

The key players in terms of financial and intellectual efforts are the CEA, CNRS and IFP. The main public research bodies are: CEA, CNRS, INERIS (Institut National de l'Environnement industriel et des RISques), universities, the INRETS (Institut National de Recherche sur les Transports), CNRT (Centre National de Recherche Technologique) in Belfort-Montbéliard and a few engineering schools (Ecole des Mines, CNAM).

Germany

- *One of the European and world leaders in hydrogen and fuel cell technology development and implementation worldwide.*
- *The "Programme on Investment into the Future" (ZIP) was started in 2001 to focus on fuel cell development and demonstration.*
- *"The Clean Energy Partnership" is an alliance between the government and major auto manufacturers to demonstrate hydrogen as a transportation fuel.*
- *The Bavarian "Hydrogen Initiative," includes the Munich Airport Project, the first public hydrogen station worldwide.*
- *German fuel cell and hydrogen storage industry is the market leader in Europe with a number of small and large companies.*
- *70 percent of today's European fuel cell demonstration units are located in Germany.*
- *RD&D has been concentrated on fuel cells since 1995 with an annual BMWA budget of €8-10 million per year.*
- *Strong participation in the European Commission research activities (Framework Programs) and other international contexts.*

Overview

Germany is at the forefront of hydrogen and fuel cell technology development and implementation worldwide. Various federal and regional initiatives are in place and there are numerous co-operations between public and private enterprises, for example the development of the MCFC technology for stationary application or the demonstration of the NEBUS and Citaro fuel cell buses from DaimlerChrysler. Other examples are the Clean Energy Partnership in Berlin, an initiative of the Federal Ministry of Traffic, Building and Housing (BMVBW) for demonstrating a hydrogen service station and hydrogen powered vehicles. Another key initiative is the Transport Energy Strategy (TES), aimed at developing a strategy for the introduction of a new energy carrier to the transport sector.

Within the Federal Programme for "Energy Research and Energy Technologies" (Energy Research Programme) the Federal Ministry of Economics and Labour (BMWA) supports research, development and demonstration (RD&D) of fuel cells and hydrogen technologies. Intensive RD&D on hydrogen technologies started in Germany in 1988 and was concentrated on the development of specific technologies like hydrogen production using electrolysis, hydrogen storage and on large projects to demonstrate the complete supply chain of a solar hydrogen energy economy (HYSOLAR and the Solar-Hydrogen-Bavaria Project BAYSOLAR). This work was concluded in 1995-1999 with the result that in principle the main components of a hydrogen energy system were developed and functioning, however, commercial viability of a solar hydrogen economy could only be reached in the far future. As a consequence, RD&D has been concentrated on fuel cells since 1995 with an

annual BMWA budget of €8-10 million per year. Ambitious projects concentrating on new materials, improved components and system integration have been supported.

The "Programme on Investment into the Future" (ZIP – part of the Energy Research Programme) was started in 2001 to focus on fuel cell development and demonstration. Some projects related to hydrogen technology such as demonstration of infrastructure for fuel cell buses are also included. Within ZIP more than 40 additional projects are being funded by BMWA. Several 250 kW MCFC, one plant with SOFC tube concept technology, and several PEM (2-5 kW) for house applications are in operation or in a planning phase. Projects for the demonstration of fuel cell buses (Stadt Barth, Berlin) and the development of a fuel cell car (AUDI) are also included. Under the EU CUTE project the demonstration of hydrogen infrastructure for the DaimlerChrysler fuel cell bus NEBUS/Citaro is being co-financed within ZIP.

"The Clean Energy Partnership" is an alliance between the BMVBW and nine companies including car manufacturers BMW, DaimlerChrysler, Ford, MAN, Opel, the Berlin Transit Agency, gas supplier Linde, and ARAL. The partnership aims to demonstrate the usability of hydrogen as a transportation fuel. The project will last four years during which a hydrogen filling station will be constructed by Germany's major motor fuel distributor ARAL.

Other noteworthy programmes from the Federal States include Bavaria's "Hydrogen Initiative" and the North-Rhine Westphalia "Hydrogen and Fuel Cell R&D Programme." Both are being funded at a rate of €7-10 million per year. And, in 2003, BMWA established an advisory council on hydrogen technologies with the objective to draw up a new vision on future RD&D demand.

Priorities and Targets

- The Transport Energy Strategy (TES) is a joint project undertaken by the BMVBW, motor vehicle manufacturers BMW, DaimlerChrysler, MAN, Opel and Volkswagen, and energy supply companies ARAL, BP, RWE and Shell to introduce alternative fuels for broad-based use in transport. The project's results indicate that hydrogen is the most promising transportation fuel in the long term.
- Since the end of the large hydrogen demonstration projects in 1995-1999, public funding of the BMWA was concentrated on RD&D for fuel cells. In accordance with industry and to achieve the best possible efficiency for the use of public budgets, RD&D is focusing on the following fuel cell technologies:
  - Proton Exchange Membrane Fuel Cell (PEM) and Direct Methanol Fuel Cell (DMFC);
  - Molten Carbonate Fuel Cell (MCFC);
  - Solid Oxide Fuel Cell (SOFC).

Despite the very promising results, further RD&D activities are necessary to develop fuel cell technologies viable for commercial application. The main obstacles for market penetration of these technologies are high costs and low lifetime of the systems. Due to these obstacles, technological development and introduction into the market implies high risk, thus justifying public support of RD&D measures. For future activities the following conditions are being considered:

- All fuel cell technologies mentioned above have to be taken into consideration in the future RD&D programme. The main goals are cost reduction, increased lifetime and better reliability for the crucial components and systems.

- Up to now large industrial companies were the main players in developing fuel cell and hydrogen systems. In approaching the market introduction phase, small and medium-sized companies have to be prepared as suppliers of components, like reformer systems, stack components, inverters or hydrogen storage systems. For these components, further development is needed for the manufacturing of sophisticated fuel cells and hydrogen systems with high performance and long life time.
- Qualification measures are needed for preparing the market introduction. Codes and standards have to be developed. Within this phase, RD&D activities have to embrace the whole technology chain beginning with the fuel infrastructure and including gas reforming, fuel cell, fuel storage, operation and maintenance of the system.

Programme activities

Within the German Energy Research Programme of the Federal Government, RD&D activities on fuel cell technologies have a high priority. Except for some minor activities within the ZIP program, BMWA does not currently subsidise major RD&D activities on hydrogen technologies. However, a vision on future RD&D demand on hydrogen technologies is being drawn up by an advisory council and will be published in the second half of 2004. The following RD&D efforts are considered for further development of fuel cell technologies:

- **PEM fuel cells.** R&D will be concentrated on the optimisation of well known technologies as well as on new, promising technological concepts. The following investigation areas are foreseen in a time period of 5 years:
  - Optimisation of performance – including: (a) catalytic materials with higher CO tolerance; (b) development of cell design with higher integrity of the components; (c) increase of the operation temperature of the stacks with influence on operation strategies and membrane materials; (d) increase of efficiency and decrease of size of the components.
  - Decrease of cost – including: (a) development of catalytic materials with higher yield and decreased cost; (b) development of new materials for bipolar plates allowing lower production cost; (c) development of new membrane materials; (d) development of cost effective sealing concepts and sealing materials.
  - Development of reformer technology – including: (a) application of micro structure technology to reduce the size of components; (b) increase of stack temperature to facilitate the thermal integration of the reformer system; (c) accelerated and efficient warm up of the reformer system.
- **MCFC fuel cells.** The focus for future R&D efforts on MCFC is the investigation of materials to increase life time and reduce production cost. The development of MCFC systems in Germany is based on the "Hot-Module" system by the company MTU CFC Solutions GmbH. This fuel cell technology is in a very advanced status. Nevertheless, changes of the cell design are needed to simplify the production process in order to reduce costs further. The main R&D efforts for reaching these goals are:
  - New sealing concepts;
  - New processes allowing series production;
  - High temperature, corrosion resistant metallic materials;
  - Developments of sub systems like inverters, fuel reforming, pumps etc.;
  - Development of new designs for series production which is planned for 2004.

- **SOFC fuel cells.** R&D activities will be concentrated on research on new materials and designs for a next fuel cell generation with lower production cost. Germany reported that the following R&D measures are crucial for the next generation of SOFC:
  - Development of HPD-SOFC tubes (High Power Density) with 1/3 of ohmic resistance and half of the size of known technologies. Progress in this field could open the tubular technology to small scale applications, such as the combined generation of heat and power for domestic use.
  - Development of cost effective isolation materials and heat exchangers.
  - Development of planar designs with higher power density and lower operation temperature.
  - Optimised integration of gas turbines.
- **Activities in the Federal States.** In addition to the programme of the BMWA, the following Federal States provide noteworthy programmes for hydrogen and fuel cells RD&D:
  - The Bavarian "Hydrogen Initiative," includes the Munich Airport Project, the first public hydrogen station worldwide. Two different refuelling units, one for four MAN buses (three with combustion engines and one with fuel cell) and one for BMW passenger cars using liquid hydrogen were installed to gain and evaluate operation experiences.
  - The North-Rhine Westphalia "Hydrogen and Fuel Cell R&D Competence-Network" focuses the research activities on PEM and DMFC, components, stack, reforming and system development as well as on hydrogen storage and system analysis.
  - The Fuel Cell Initiative of Baden Württemberg with main activities in developing fuel cells for portable applications and in training and education.
  - HFC initiatives are also carried out in Lower Saxony and Hesse.
- **Fuels.** The treatment of fuels is crucial for high temperature and low temperature fuel cells as well. Germany is working on a number of related aspects, including: (a) improving the life time of carbon filters used for desulphurization of fuel gases; (b) cleaning biogas gases from agro-industrial wastes and sewage sludge; (c) investigating the influences of different impurities (metals) on the degradation of power density.
- **Fuel infrastructure.** The construction of fuel infrastructure, especially for mobile and portable fuel cell application has a high priority. The final decision of the investment in costly infrastructure warrants R&D activities in the following areas:
  - Development of cost effective processes for hydrogen and methanol production at a reduced level of CO_2 emissions;
  - Modelling the long term transfer to a potentially environmentally-friendly and cost-effective hydrogen economy, and creation of transition scenarios with strong dependence on coal, crude oil and natural gas;
  - Development of new storage systems for hydrogen with high capacity and high cycling rates.
- **Modelling.** Fuel cell systems are very complex. For the simulation of dynamic and degradation processes, new modelling procedures are necessary. Using these tools, the development of new cell designs could be accelerated. Those models should comprise catalytic processes, cell and stack simulation, operation strategies, and dependence of the grid connection. Especially for stationary applications, the following questions concerning the future infrastructure are being investigated:
  - Development of modelling tools for fuel cell systems and their components;

  - Investigation and modelling of degradation processes and the development of faster degradation test methods;
  - Development of operation strategies.
- **Standardisation.** The standardisation of systems is needed for accelerated development. Up to now, no unique and acknowledged evaluation criteria for fuel cells and components exists – which causes huge hurdles for new players in this technology area. Safety aspects need to be fitted to the emerging fuel cell technology. International standards must be generated.
- **Inverter.** Development of new inverter systems for the integration of fuel cells into the electricity grid with high efficiency and in different power units (0.5-250 kW) are necessary.
- **Recycling concepts for fuel cell components.** Since fuel cells include valuable materials, recycling practices should be developed and demonstrated, including:
  - Development of recycling concepts for PEMFC with emphasis on recovery of catalyst materials used for stack and reformer;
  - Development of recycling concepts for MCFC with focus on recycling of the used fuel cell components;
  - Development of recycling concepts for SOFC with concentration to the cathode containing costly lanthanum, the recovery of nickel and the recycling of the metallic components.

Budget

Federal Government

Public funding of BMWA for fuel cell RD&D amounts to €8-10 million annually. Within the "Programme on Investment into the Future," an additional €15 million per year have been granted for fuel cell projects during the period 2001-2003. Basic research on fuel cells in the Helmholtz research centres is supported by the Ministry of Research and Education, which amounts to €15 million per year. The "The Clean Energy Partnership," was initiated in 2004 with a total budget of €33 million, in addition to €5 million in funding from the German Federal Government.

Federal States

- **North-Rhine-Westphalia.** Since 2000, €77 million has been allocated to 42 different projects, primarily fuel cells R&D.
- **Bavaria.** €75 million has been allocated to 30 Projects, primarily fuel cells R&D.
- **Baden Württemberg.** Funding of fuel cells R&D amounts to about €5-6 million per year.

Key Players

Federal Government

- Ministry of Economics and Labour (BMWA).
- Ministry of Research and Education (BMBF).
- Ministry of Traffic, Building and Housing (BMVBW).
- Research Centre Jülich, Project Management Organisation Jülich (PtJ).

Research Centres

- Deutsche Zentrum für Luft- und Raumfahrt (DLR).
- Forschungszentrum Jülich GmbH.
- Fraunhofer Gesellschaft (FhG).
- Zentrum für Sonnenenergie und Wasserstoffforschung (ZSW).

The German fuel cell industry

It is probably fair to say that the German fuel cell industry is the market leader in Europe, not only in terms of the number of companies involved and people employed, but also in showing leadership through a variety of demonstration projects – more than 70 percent of today's European fuel cell demonstration units are located in Germany. The strengths of the German industry as a whole lie in excellent manufacturing background, the willingness of established companies to invest money, Federal and State government sponsoring, a strong research background, and the preparedness to use foreign technology for demonstration projects.

According, a long list of leading companies comprises the German fuel cell industry.

Adam Opel
ARAL
Audi AG
Ballard
BMW Group
BEWAG
Cellanese, since 2004 PEMEAS
CeramTec
DaimlerChrysler
European Fuel Cell GmbH
Elving Klinger
EnBW
E.ON Energie
EWE
FuMA-Tech
GKN Sinter Metals
H.C. Starck GmbH
HEW
IPF Beteiligungsgesellschaft Berndt
Liebherr-Aerospace-Lindenberg GmbH
Linde
MTU CFC Solutions GmbH (MCFC)
Pfalzwerke GmbH
Proton Motor
Rhodius
Robert Bosch GmbH
RWE Fuel Cells GmbH
Saar Energie GmbH
Sartorius
Schunk Kohlenstofftechnik
Smart Fuel Cells
SGL TECHNOLOGIES GmbH (Bipolar Plates)
Siemens Westinghouse
Süd-Chemie
Thyssen Krupp VDM
Umicore AG & Co. KG
Vaillant GmbH (PEMFC)
Viessmann Werke GmbH & Co KG (PEM)

Other activities

- The German research concept COORETEC (CO_2 Reduction Technologies) investigates options for the generation of electricity from fossil fuels with CO_2 capture and storage which opens access to CO_2 free production of hydrogen.
- Germany is participating actively in the EU Hydrogen and Fuel Cell Technology Platform and is actively involved in the International Partnership on Hydrogen Economy (IPHE).

Greece

- ***Under the Hellenic HFC network a number of research institutions and universities work on hydrogen and fuel cell projects.***
- ***Investigating the development of "hydrogen islands" which would be applicable to the niche market of Greek islands that are not connected to the electricity grid.***
- ***Greece participates in a number of R&D activities in the context of EU co-funded projects.***

Overview

Although Greece has no specific national plan on hydrogen and fuel cells, the topics have recently been included in the Greek national research agenda of the Operational Plan of Competitiveness published by the General Secretariat of Research and Technology of the Ministry of Development. Past research activities in Greece on these two topics have been funded primarily by EC funds.

The Greek Hydrogen Association was formed in 2000 but has not been particularly active, mostly due to a lack of funds. This is changing in 2004 and the Association is organising the 1st National Conference on Hydrogen as an energy carrier in September 2004.

Greek public authorities related to the subject, namely the General Secretariat of Research and Technology (GSRT) and the Ministry of Development have recently taken an interest in hydrogen as an energy carrier. These efforts are driven largely due to the political support for hydrogen and fuel cells demonstrated by the EC, the formation of the International Partnership for the Hydrogen Economy initiated by the US, and the Hydrogen Co-ordination Group formed by the IEA/OECD. As a result, GSRT is launching a framework for the collaboration of Greek R&D institutes with counterparts in established programmes in countries outside of the EU, namely Australia, Canada, Japan and the USA.

Priorities and targets

No specific priorities and targets have been set at a national level for hydrogen and fuel cells. Priorities and targets have until recently been set at the level of each research or industrial "unit" and were most often driven by the availability of funds and not to meet strategic objectives. Hydrogen and fuel cells have, however, been included in recent national R&D programs.

Specific features of Greece in terms of its natural resources and its industrial and academic base are currently leading the Greek R&D community, in collaboration with government, to investigate the development of "hydrogen islands", which would be applicable to the niche market of Greek islands that are not connected to the electricity grid, and also to other remote communities in Europe.

Program activities

The Greek Operational Programme for Competitiveness contains work elements for "Renewable Energy Sources and Energy Saving." Among the programs, storage of hydrogen in nano-structures and the development of high-temperature PEM fuel cells are included. Total funding is €1.5 million.

Greece is also participating in a number of R&D activities in the context of EC co-funded projects. Some of these institutions have formed an informal network of laboratories and projects, as presented below. The network is currently (Feb 2004) trying to support the funding of its activities through the ERA-NET scheme of the EC.

Hellenic hydrogen and fuel cell technologies network

The following is a short description of the research institutions and related projects which form the Hellenic HFC network:

- The University of Patras works on design and synthesis of materials, characterization of materials, catalyst development and evaluation, advanced electrochemical reactors, SOFCs, electrodes, and the reforming of fuels.
- The Chemical Process Engineering Research Institute (CPERI) works on bench and pilot plant hydrogen production units, SOFCs, polymer electrolyte proton conductors, and high-temperature electrocatalytic processes.
- The Centre for Renewable Energy Sources (CRES) works on development & demonstration of systems with integrated RES & Hydrogen Technologies, Hydrogen production via high pressure electrolysis, utilizing wind energy, Hydrogen storage technologies, modelling and optimization of RES&H_2 systems.
- The National Technical University of Athens (NTUA) works on hydrogen production from waste gases, production of hydrogen from solid fuels, water-gas-shift reaction catalysts, membrane separation, gasification of solid fuels, simulation of advanced power systems based on fuel cells, and hydrogen production and infrastructure.
- The University of Thessalia Department of Mechanical and Industrial Engineering works on design, construction and testing of SOFC components, and solid oxide electrochemical reactors.
- The Institute of Chemical Engineering and High Temperature Chemical Processes (ICE/HT) works on design, construction and testing of PEM components, electrochemical reactions/reactors, electrocatalysts for PEMs, hydrogen production by catalytic processes and water splitting.
- "Demokritos" (NCSR) Institute of Materials Science works on preparation & characterization of nanostructured materials, metallic and metal – oxide contacts, preparation of thin/thick films, and hydrogen storage.

Budget

The total budget of these R&D activities is greater than €5 million.

The Greek fuel cells industry

HELBIO, Hydrogen and Energy Production Systems S.A. is planning to commercialize (early 2005) an ethanol fuel processor system for hydrogen production from biomass – derived ethanol (renewable hydrogen) for stationary fuel cell applications. The target market is remote, off-grid locations and areas of inexpensive ethanol production (Brazil, India, China, Hawaii). HELBIO is also developing a reformer for Liquefied Petroleum Gas (LPG) which will be used for hydrogen production for industrial applications. This product will be commercialized in 2006. (*http://www.helbio.com*)

The Greek company Tropical is investing in the integration of Canadian-made fuel cells in various stationary and mobile platforms like gen sets and 2- or 4-wheel mini-vehicles. (*http://web.otenet.gr/tropical/*).

Italy

- ***Extensive R&D work across the board on hydrogen production and storage and on fuel cells, focussing on PEM, MCFC and SOFC.***
- ***Extensive participation in a number of internationally-sponsored and EU-sponsored programmes.***
- ***Cooperation with research institutes, universities and industry.***
- ***Highlight: the "Bicocca Project" is an integrated project for hydrogen development in urban areas.***
- ***Government investment in HFC is approximately €30 million per year.***

Overview

Italy has invested in hydrogen and fuel cell technology development since the early 1980s. At the time, R&D activities concentrated on the development of fuel cell technologies, while a moderate R&D commitment was addressed towards the production of hydrogen as sustainable energy carrier. In the beginning of the 1990s, projects were carried out for the production of hydrogen from renewable energy sources and its utilisation in internal combustion engines (ICE). Italy's ENEA laboratories have developed an integrated plant for the production of hydrogen from photovoltaic sources, its storage and utilisation in fuel cells. This plant has been built and tested under the auspices of various EU frameworks.

In more recent years, industrial involvement has increased in the development of hydrogen vehicles, under the auspices of either national or international programs. In February 2001, Fiat introduced its first prototype of a fuel cell car, the "Seicento Elettra H_2 Fuel Cell" and a more advanced prototype of the same car was presented in 2003. Both Fiat prototypes use compressed hydrogen as fuel on board and fuel cell stacks supplied by Nuvera.

A national R&D Program on "Hydrogen and Fuel Cells" – supported by the Ministry of Research and University and the Ministry of the Environment – was outlined in the framework of the National Research Plan (PNR). Under this programme, in March 2003, the Ministry of Research launched the first call for proposals on "New systems for energy production and management." The general aim of the activity is the development of knowledge and innovative solutions to advancing hydrogen and fuel cell technologies in the early stages of development. Italy is active in international cooperative agreements, and is at the forefront of many EU fuel cell and hydrogen initiatives.

Priorities and targets

The following areas have been identified as priorities for hydrogen as a sustainable energy carrier:

- Development of technologies, components and innovative systems for hydrogen production from renewable sources or from fossil fuels, and hydrogen/CO_2 separation.

- Development of systems for hydrogen storage.
- Study of CO_2 sequestration in geological sites and development of related technologies.
- Development of technologies, components and systems for use of hydrogen in transport sector and for distributed generation.

The R&D priority areas related to fuel cell technologies are:

- Improvement of performances and cost reduction through the development of innovative materials, components and cell design.
- Development and demonstration of fuel cell systems for transportation, stationary power generation and portable units.
- Plant demonstration, monitoring and verification of operative behaviour of cells using different fuels.

Program activities

Activities in hydrogen and fuel cells are increasing within the framework of national and European programs. Currently, around 250 people are engaged in fuel cell activities, about half of them from industry.

The definition of R&D activities, shared by public organisations (research institutions, universities) and national industries (oil companies, electric and gas utilities, research groups) is still in progress.

The proposals selected for financing within the PNR Programme (FISR 2003-2005) include:

Hydrogen production

- Micro-combustor matrices for hydrogen. Activity leader: FIAT Research Centre (CRF). Estimated activity cost: €8.7 million.
- Hydrogen production and storage in nano-materials. Activity leader: Consortium of Italian universities for the development of large inter-phase systems. Estimated activity cost: €6.3 million.
- Innovative systems for hydrogen production from renewable sources. Activity leader: IPASS Consortium. Estimated activity cost: €10 million.
- Integrated systems for hydrogen production and its utilisation in distributed generation. Activity leader: Consorzio Pisa Ricerche. Estimated activity cost: €7.9 million.
- Innovative processes and technologies for the transition phase and for the preparation of future hydrogen based energy systems. Activity leader: ENEA. Estimated activity cost: €15.2 million.
- Pure hydrogen from light multi-fuels by total conversion reformers and storage in porous matrices. Activity leader: University of L'Aquila. Estimated activity cost: €9.9 million.
- Innovative methods for hydrogen production from biological processes. Activity leader: University of Padova. Estimated activity cost: €7.9 million.
- Hydrogen production from petrochemical refineries wastes and its utilisation in power train for railway vehicles and in distributed generation of electricity. Activity leader: University of Perugia. Estimated activity cost: €6.9 million.

Fuel Cells

- Polymer electrolyte membrane and solid oxide fuel cells: demonstration of systems and development of new materials. Activity leader: National Research Council (CNR). Estimated activity cost: €14 million.
- Development of various fuel cell technologies and systems for their applications. Activity leader: ENEA. Estimated activity cost: €10.8 million.
- Inorganic and hybrid nano-systems for the development and the innovation of fuel cells. Activity leader: Consortium of Italian Universities for the Science and Technology of Materials (INSTM). Estimated activity cost: €6.3 million.
- Development of a pressurized MCFC plant and testing of a 500 kW demonstration plant fuelled with syngas. Activity leader: University of Genoa. Estimated activity cost: €7.2 million.
- New systems for molten carbonate fuel cell of low cost for distributed generation. Activity leader: University of Perugia. Estimated activity cost: €10.8 million.
- Development of proton exchange compound membranes and innovative electrode configuration for PEM fuel cells. Activity leader: University of Rome "La Sapienza". Estimated activity cost: €6.2 million.

Demonstration Projects

Various demonstration projects and activities have been planned and implemented to field-test key hydrogen technologies and to help potential end-users and the general public to recognise the benefits and opportunities of hydrogen and fuel cell technologies. Examples of significant initiatives include:

- Currently, fuel cell activities are focused on the development and demonstration of various technologies including PEMs for stationary and automotive applications; MCFCs for on-site and distributed generation; and some research on materials and components for SOFCs.
- The "Bicocca Project" is an integrated project for hydrogen development in urban areas. It has been set-up as a demonstration project by the Milan Municipality and Lombardy Region. In particular, the Project is important as being located in the city and will provide valuable information on how to carry out hydrogen penetration in urban areas. This project is partially funded by the Ministry of the Environment (about €4.6 million) with a total estimated activity cost of around €20 million.
- A few demonstrations of phosphoric acid fuel cells were carried out to evaluate and validate the performance and durability of small on-site co-generation systems, including 50 kW at Eniricerche in Milan and 200 kW at ACoSeR in Bologna.
- A 1.3 MW demonstration plant for utility applications was constructed by Ansaldo Ricerche, in cooperation with ENEA and AEM (the Municipal Energy Authority of Milan), and tested in Milan. Project activities were stopped in 1997 due to significant difficulties in reducing cost to the level needed for introduction into the market (1,000-1,500 €/kW).
- The first hydrogen-powered urban fuel cell bus was developed by IVECO/IRISBUS for the municipal transport authority of Turin, in 2001. The bus, in hybrid configuration, is fuelled with hydrogen (via electrolysis) and equipped with a battery system. The fuel cell, supplied by International Fuel Cells, has a power of 60 kW.

Current Projects

Several projects are currently being implemented under the auspices of national and EU programs. Examples of projects include:

- **Development and testing** of a 15 kW power generating system using PEM fuel cells for electric vehicles. Activity cost: €3.15 million (€1.725 million from ENEA). Partners: Nuvera Fuel Cells Europe, CNR-ITAE, Polytechnic of Milan, Universities of Genoa and Rome.
- **Construction and testing** of a 30 kW hybrid system including 5 kW PEM fuel cell stack for propulsion purposes. Activity cost: €0.5 million.
- **Development of PEM stack and components** (1-5 kW). Activity cost: €0.6 million. Partner: Arcotronics Fuel Cells. Construction of a 1 kW stack with novel solutions and low cost; development of a fuel processing system. Partner: ENEA, Arcotronics Fuel Cells, Research Institutions. Systems: development of key components (fuel processing systems, controlling systems, auxiliaries); construction of prototypes and testing. Budget: €2.88 million. Partners: ENEA, Arcotronics Fuel Cells, Universities and CNR.
- **Development of MCFC cell, stack and system components.** Improvement of efficiency and durability and cost reduction of MCFC systems through optimization of cell and stack components; cost-benefit analysis to overcome the technical and economic barriers to the development and employment of MCFC. Budget: €2.6 million. Partners: ENEA, Ansaldo Fuel Cells Co, CNR-ITAE, CESI, Universities of Perugia, Messina and Genova.
- **Development of storage systems with metal hydrides for FCV:** R&D of novel Mg-based metal hydrides; design and engineering of a working prototype based on conventional AB5 metal hydrides; process development and production of specialized metal hydrides (high energy density and high cyclability); bench test and in-vehicle testing. Budget: €1.55 million. Partners: ENEA, SAES Getters, CNR-ITAE, Universities.
- **Development of carbon-based materials** (nanostructures): materials preparation and optimization through chemical and physical characterization and molecular modelling. Partners: ENEA, ELETTRONAVA, Universities. Budget: €1.24 million.

Budget

Over the last three years, national public funding amounts to approximately €90 million – of which €51 million is available for hydrogen and €39 million for fuel cell development and deployment. Most related projects are cost-shared with the private sector, and as such the overall budget can be estimated at roughly €130 million, corresponding to a yearly budget of close to €43 million.

Key players

Key players in Italy's fuel cell and hydrogen sector span public and private entities including active participation from technical universities and research centres.

- Public authorities: the Ministry of the Environment; Ministry of Production Activity; Ministry of Research and University; Regional governments (Lombardia, Piemonte, Tuscany, Veneto) and local authorities (Municipality of Florence, Municipality Mantova, Municipality of Milan).

- Public research institutions: ENEA, National Research Council (CNR) Institutes: CNR-ITAE, CNR-IENI, CNR-IMM, CIRPS.
- Technical centres: CESI; Venezia tecnologie.
- Universities: Genova, L'Aquila, Messina, Milano, Pavia, Perugia, Roma, Siena, Torino, Trento.
- Urban Buses Services: ATM Turin, ATAF Florence.

The Italian fuel cells industry

Research and development activities, including novel hydrogen production routes, storage and delivery technologies and infrastructures are carried out through close cooperation with public research institutes and industry. Key companies include Air Liquid Italy, Ansaldo Fuel Cells Co, Ansaldo Ricerche, Arcotronics Fuel Cells, EniTecnologie, Fiat Research Center, IVECO-Iribus, Nuvera Fuel Cells Europe/DNTE, Pirelli Labs, SAES Getters, SAPIO, SOL, Technip/KTI and several other SMEs.

International Cooperation

Italy also reports extensive participation in a number of internationally-sponsored and EU-sponsored programmes. These include, but are not limited to:

- PIP-SOFC – Pressurized IP-SOFC: a path to successful SOFC/Hybrids.
- IRMATECH – Integrated research on materials, technologies and processes to reduce costs of MCFC through a cost reduction in materials and manufacturing processes; improve the compactness and increase the stack lifetime; and, minimise the environmental impact and used energy relating to some manufacturing processes.
- TWINPACK – The purpose of the project is the design, construction and testing of a pressurised MCFC Clean Power and Heat Cogeneration Compact Plant, sized for a power output up to 500 kW.
- MOCAMI – Development and demonstration of a MCFC hybrid power plant toward low-cost production. The project combines MCFC technology and micro gas turbine (MGT).
- FRESCO – Fuel Cell Scooter – green option for urban mobility. The main objective of this project is to prove the viability of the clean cell propulsion for small vehicles, by developing a dedicated system and by integrating it in a modern mass-production scooter. The technological achievements comprise a compact water-cooled PEM fuel cell stack, a supercapacitor peak-power device, and an innovative electric motor and traction converter allowing for regenerative braking.
- CityCell – Fuel cell energy in cities. This projects demonstrates five fuel cell-hybrid electric vehicles in Turin, Berlin, Madrid and Paris.
- PEM ED – To develop thermally stable protonic membranes based on sulfonated polymers and hybrid inorganic-organic systems that can be produced on an industrial scale.
- DREaMCAR – The primary objective of the project is to develop highly efficient, low emission automotive fuel cell propulsion systems that meet customer requirements in terms of cost and performance.

- BIOFEAT – Development of a biodiesel processor for an on-board fuel cell APU. The expected result is a fully tested modular 10 kW biodiesel fuel processor for an SOFC or PEM APU for a vehicle.
- BIO-H_2 – Producing clean hydrogen from bioethanol.
- CLEAN ENERGY FROM BIOMASS – The project is addressed at demonstrating the industrial feasibility of the integration of biomass steam gasification with a MCFC for clean and renewable power generation.

Japan

- *One of the world leading programs focused on early commercialisation of fuel cells in close partnership with the national industry.*
- *The International Clean Energy Network Using Hydrogen Conversion (WE-NET) programme was the first major, national HFC R&D programme.*
- *The "New Hydrogen Project" for the commercialisation of hydrogen fuel cells 2020, integrates the development of fuel cell, hydrogen production, and hydrogen transportation and storage technologies, concurrently with demonstration programs, vehicle sales, construction of refuelling infrastructure, establishment of codes and standards, and a general push to enlarge the consumer market for fuel cells and fuel cell vehicles.*
- *The JHFC (Japan Hydrogen Fuel Cell) Demonstration Project consists of road test demonstrations of FCVs and the operation of hydrogen refuelling stations.*
- *HFC R&D work across the spectrum of fuel cell types and auxiliary components. Focus on PEM and large-scale MCFC and SOFC, and on micro DMFCs for portable applications.*
- *Japanese manufacturers are among the world leaders in HFC R&D, manufacturing, demonstration and commercialisation.*
- *Annual investment in HFC programmes is approximately ¥30 billion:*
- *Commercialisation Targets:*
  - *2010: 50,000 FCVs; 2 GW stationary FC.*
  - *2020: 5,000,000 FCVs; 10 GW stationary FC.*

Overview

Japan has been an early leader in hydrogen and fuel cell technology development. Since the early 1980s, Japan has invested in research and development into various fuel cell technologies, beginning with PAFCs and MCFCs. Research and development of PEFCs was launched in 1992, and is the focus of Japan's fuel cell research program. The investment to date has amounted to some ¥97 billion.

In 1993, Japan launched WE-NET, the International Clean Energy Network Using Hydrogen Conversion, which initially focused R&D on core technologies necessary for establishing a hydrogen infrastructure (e.g., electrolysis, liquefaction, storage) and then later on the utilization of hydrogen and construction of fuelling stations. The ten-year, ¥18 billion yielded several successes (see below) and is succeeded by a set of new projects which are now elements of METI's "New Hydrogen Project" for the commercialization of hydrogen fuel cells.

The New Hydrogen Project (NHP) extends the work initiated in WE-NET and ties together a number of METI's ongoing and new programs. In particular, it recognizes that in addition to fuel cell

technology development, it is necessary to establish technology on the safe use of hydrogen and to promote policy measures such as establishing codes, standards and regulations in order to bring fuel cells to the market.

In the area of fuel cell development, a "Policy Study Group for Fuel Cell Commercialisation", which consists of various members from industry, academic and public organizations, was established in December 1999. Following several studies and a March 2001 Fuel Cell Commercialisation Conference, a strategy emerged for the practical application and implementation of fuel cell technologies. The strategy is a based around a three-stage commercialisation plan through 2020, which integrates the development of fuel cell, hydrogen production, and hydrogen transportation and storage technologies, concurrently with the implementation of demonstration programs, vehicle sales, construction of refuelling infrastructure, establishment of codes and standards, and a general push to enlarge the consumer market for fuel cells and fuel cell vehicles.

Taken together, and building upon the foundations laid by WE-NET, Japan is now undertaking one of the most ambitious and comprehensive HFC initiatives in the world.

Commercialisation phases

According to the Ministry of Economy, Trade and Industry's (METI) commercialisation strategy, 2002-2005 will focus on continued technology development, vehicle and stationary fuel cell demonstrations, development of soft infrastructure and codes & standards, and the establishment of fuel standards. The period from 2005-2010 is to be the Introduction Stage, when the introduction of vehicles will be accelerated along with the gradual establishment of the fuel supply system. Finally, the Diffusion Stage will encompass initiatives taken forward from 2011, particularly the establishment of the fuel supply system and "self-sustained growth" driven by private sector promotion and adoption.

Fuel cell performance targets:

Fuel Cell Vehicles	Stationary Fuel Cells
Stack: Power generation efficiency over 65% (LHV) and over 55% (HHV)	**Stack:** Power generation efficiency over 55%
Tank to wheel efficiency: Hydrogen loading type – approx. 60% (LHV), approx. 51% (HHV) Gasoline loading type – approx. 48% (LHV), approx. 45% (HHV)	**System:** Power generation efficiency over 40% (HHV); total efficiency over 80% (HHV); durability over 40,000 hours
Cost: below 5,000 yen/kW	**Cost:** Home use below 300,000 yen/system; business use below 150,000 yen/kW
Hydrogen storage: On vehicle 5 kg hydrogen storage (over 500 km cruising)	

Commercialisation targets which will drive the strategy through 2020:

By the end of the Introduction Stage in 2010:

- 50,000 fuel cell vehicles.
- 2.2 GW of stationary fuel cell co-generation systems.

By the end of the Diffusion Stage in 2020:

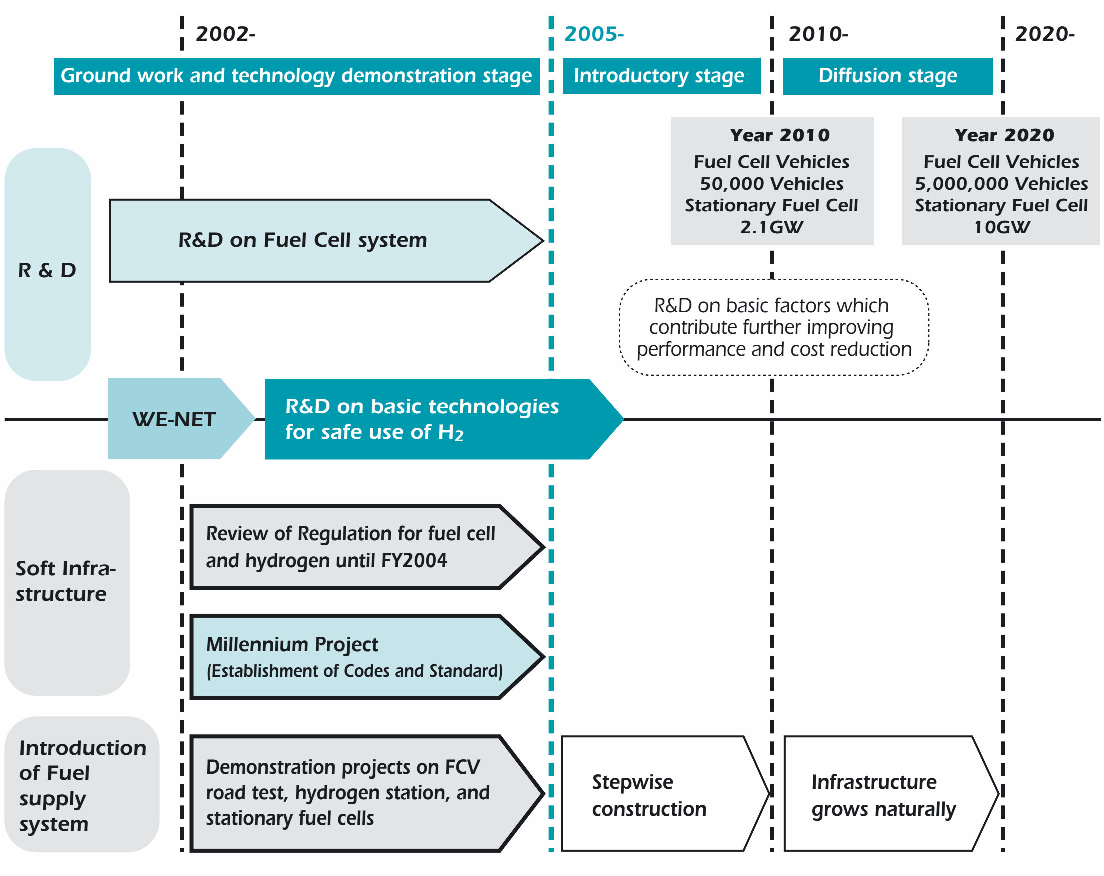
- 5,000,000 fuel cell vehicles.
- 4,000 hydrogen stations.
- 10 GW of stationary fuel cell co-generation systems.

Key components of Japan's commercialisation strategy

Japan's current strategy for commercialising fuel cells is comprised of a number of new programs and the continuation of some ongoing efforts, which integrate the development of fuel cell technologies with efforts to prepare the market for hydrogen.

Figure 7

Scenario for Practical Application and Diffusion of Fuel Cell Vehicle and Stationary Fuel Cell

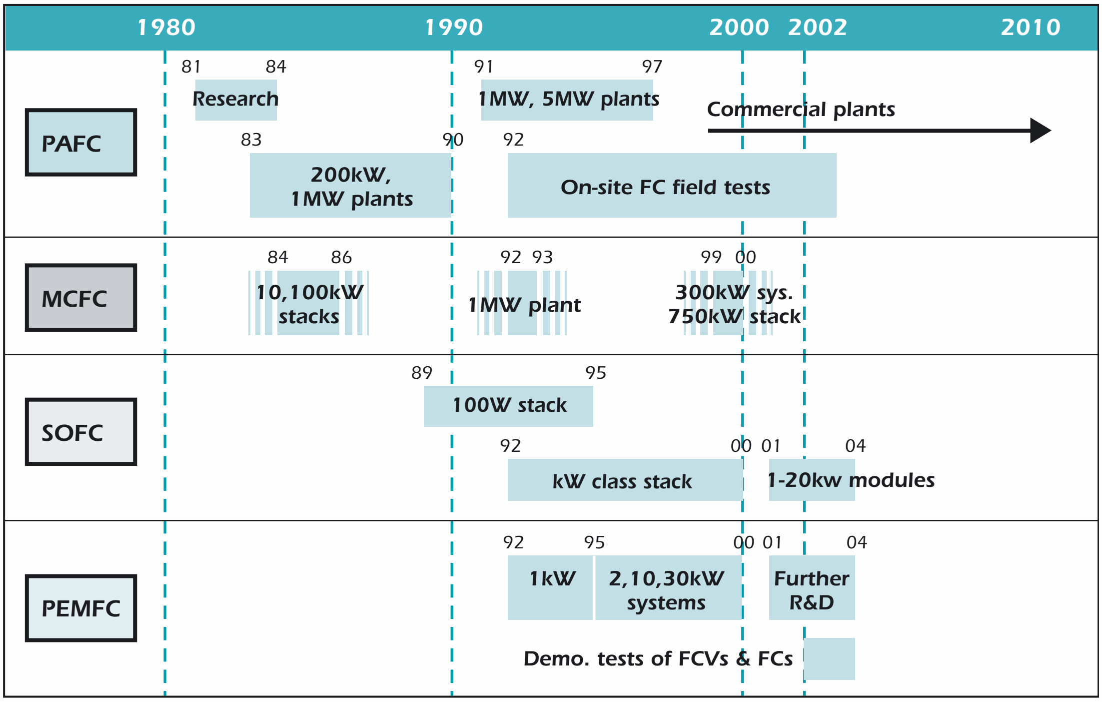


Programme activities

This section lays out the five main program components and lists the projects related to each.

Figure 8

National Projects in Japan



Continued R&D on fuel cells and systems

- **R&D on PEFC System.** METI and NEDO will continue R&D on fuel cells to meet performance targets, durability, and cost reductions toward future commercialisation, primarily focusing on PEFCs, R&D for relevant system and production technologies, and components such as membrane, electrode, MEA and separators. The budget allocations for 2001-2003 total ¥14.7 billion; the 2003 allocation is ¥5.11 billion.
- **R&D on PEFC using LP Gas.** Since LP Gas is one of the major sources for the households in Japan, the project focuses on using its availability for fuel cells. R&D will be conducted on fuel processing and evaluation of stationary PEFC system for LP Gas, including desulphurisation, fuel reforming on continuous operation and DSS pattern, steam and thermo-neutral (auto-thermal) reforming, and membrane reformers. The budget allocations for 2001-2003 total ¥0.7 billion; the 2003 allocation is ¥246 million.
- **R&D on Fundamental Technology for Fuel Cells.** This project is aimed at fundamental R&D for fuel cell development and is conducted by national institutes (e.g. the National Institute of Advanced Industrial Science and Technology). Basic technology research will be conducted in order to achieve drastic upgrades in materials and system components. The budget allocations for 2001-2003 total ¥1.8 billion; the 2003 allocation is ¥726 million.

- **R&D on Power Generation by MCFC and SOFC.** This project aims to commercialise MCFCs and develop an SOFC module. The MCFC project focuses R&D on high performance and high pressure stacks technologies as the basis of power generation and co-generation. The SOFC project focuses R&D on module cost reduction and reliability verification. Work is conducted by METI/NEDO. The budget allocations for 2000-2003 total ¥12.5 billion; the 2003 allocation is ¥3.59 billion.
- **R&D on Lithium-ion Battery for FCVs.** In order to complement fuel cell development and to advance efficiencies of FCVs, this project focuses on the commercialization of high efficiency and high-power rechargeable lithium-ion batteries. Work is conducted by METI/NEDO. The budget allocations for 2002-2003 total ¥2.9 billion; the 2003 allocation is ¥1.95 billion.
- **R&D on Mobile Fuel Cell.** This project focuses on developing fuel cell technologies (typically DMFC) to generate electricity for mobile equipment such as mobile phones, electronic terminals, and other mobile power supplies. The project covers R&D on components, manufacturing system and evaluation. The 2003 budget allocation is ¥2.2 billion.

R&D on Hydrogen

- **Development of basic technologies for the safe use of H_2.** This project is an extension of work elements conducted under the first two phases of WE-NET. The work program includes a number of diverse objectives, including the development of safety technologies for fuel cell vehicles and hydrogen refuelling stations; R&D on hydrogen production, storage, delivery in order to increase efficiency and reduce cost for hydrogen usage will be developed; and, basic R&D on advanced technologies, including hydrogen production through water photolysis. Work is conducted by METI/NEDO and private sector participants PEC and JARI. The 2003 budget allocation is ¥4.5 billion.
- **R&D on Hydrogen Production from Steel Mills.** This project is aimed at capturing the considerable volume of hydrogen gas which can be obtained as a by-product steel production. R&D will focus on the purification process of fuel from coke oven gas to an acceptable level for fuel cell utilisation. Work is sponsored by METI, the Japan Research and Development Centre for Metals and Nippon Steel. The budget allocations for 2001-2003 total ¥1.6 billion; the 2003 allocation is ¥549 million.
- **R&D Project on Highly Efficient Ceramic Membranes for High-Temperature Separation of Hydrogen.** In order to obtain a high purity of hydrogen by reforming from fossil hydrocarbon fuels, this project focuses on the development of a highly effective separation membrane with microporous ceramics. Work is sponsored by METI/NEDO/AIST. The budget allocations for 2002-2003 total ¥1.1 billion; the 2003 allocation is ¥520 million.
- **R&D on Hydrogen Purification from Gasified Coal (EAGLE).** The objectives of the EAGLE project are development of an optimum coal gasifier for fuel cells and establishment of a gas clean-up system for purification of coal gas to the acceptable level for utilization for MCFC and SOFC. The budget allocations for 2000-2003 total ¥4.6 billion; the 2003 allocation is ¥1,000 million. Work is sponsored by METI and the Electric Power Development Co., Ltd.

Regulations

This program is oriented toward creating regulations suitable for market introduction of FC using hydrogen by 2005. It involves liaison between government (Cabinet Secretariat, Cabinet Office, National Police Agency, Fire and Disaster Management Agency, Ministry of Environment, METI and MLIT) and industry. The review will include 28 regulations and 6 laws (High Pressure Gas Safety

Law, Electricity Utilities Industry Law, Traffic Law, Road Tracking Vehicle Law, Fire Law and Building Standard Law).

- **Development of basic technologies for the safe use of H_2.** Sub theme: Development of hydrogen safety technologies for practical utilisation. In order to contribute the review of regulations, technology on safe use of hydrogen for fuel cell vehicles, hydrogen refuelling stations and other fundamental research will be developed by 2005. The 2003 budget is ¥4.5 billion, including R&D on hydrogen.
- **Establishment of codes and standards (Millennium Project).** In order to promote the establishment of codes and standards, the project focuses on R&D on testing methodologies and data acquisition for PEFC vehicles and stationary PEFC systems. The goal is to promote international standardisation, fuel standard studies, establish performance and safety testing methods for public use, and reviewing of regulations. The 2003 allocation is ¥3.87 billion.

Fuel cell and hydrogen demonstration programs

- **Japan Hydrogen & Fuel Cell Demonstration Project (JHFC).** The JHFC Demonstration Project consists of road test demonstrations of FCVs and the operation of hydrogen refuelling stations. In this project, ten hydrogen stations with various fuel sources will be tested, such as de-sulfurized gasoline reforming, naphtha reforming, LP Gas reforming, liquid-hydrogen storage (from by-product of steel mills), methanol reforming, mobile stations, water electrolysis, kerosene reforming, natural gas reforming and high-pressure storage (from by-product of sodium hydroxide, NaOH). These stations will be operated and evaluated along with the FCVs that participate in this project. Moreover, forty-eight FCVs and five fuel cell buses from domestic and overseas car manufacturers are participating in this project and various data such as driveability, environmental characteristics, fuel consumption will be obtained for evaluation. The budget allocations for 2002-2003 total ¥4.5 billion; the 2003 allocation is ¥2.56 billion.
- **Stationary Fuel Cell Demonstration Project.** In order to estimate the efficiency and identify the problems of commercialization of stationary PEFC, this project operates 31 stationary fuel cells in various sites such as residential areas, heavy traffic areas, and seaside areas. It will also evaluate various fuel types (i.e. natural gas, LP Gas and kerosene). The budget allocations for 2002-2003 total ¥1.8 billion; the 2003 allocation is ¥1.3 billion.
- **Demonstration Project on Distributed Power Generation and Grid Connection.** In order to introduce distributed energy systems, such as solar, wind and fuel cell, it is necessary to optimise the fluctuation of the output. Therefore, this project operates solar, wind and fuel cell (typically MCFC) simultaneously by using information technology (IT) and establishes technologies for minimizing fluctuations. The budget allocation for 2003 is ¥3.48 billion.

Budget

In 2002, METI's budget for Fuel Cell and Hydrogen development amounted to ¥22 billion:

- WE-NET: ¥2.9 billion.
- MCFC and SOFC: ¥3.3 billion.
- Hydrogen production: ¥4.9 billion.
- PEMFC: ¥8.6 billion.
- Fuel cell and hydrogen demonstration programs: ¥2.5 billion.

The 2003 budget was increased substantially to ¥31 billion:

- Continued R&D on Fuel Cells and systems: ¥13.8 billion.
- Establishment of codes and standards (Millennium Project): ¥3.9 billion.
- R&D on basic technologies for the safe use of hydrogen: ¥4.5 billion.
- Fuel cell and hydrogen demonstration programs (vehicles, refuelling and stationary applications): ¥7.3 billion.

Key players

- METI: Much of Japan's hydrogen and fuel cell program is guided and funded by the Ministry of Economy, Trade and Industry (METI).
- NEDO: New Energy and Industrial Technology Development Organisation (NEDO) is researching and developing hydrogen energy technologies in a joint industry-government-university effort, aiming at worldwide deployment by the year 2030.
- The Policy Study Group for Fuel Cell Commercialisation.
- The Fuel Cell Commercialisation Conference of Japan.

Review of the WE-NET project

In 1993, the Agency of Industrial Science and Technology (former AIST) in the Ministry of International Trade and Industry (MITI) launched the project entitled International Clean Energy Network Using Hydrogen Conversion (WE-NET: World Energy Network). Phase One of the WE-NET project was aimed at the establishment of the basic research and development on fundamental technologies necessary for optimisation of the energy network system. This work included a variety of hydrogen production, storage/transportation and utilisation technologies such as:

- Assessment of hydrogen energy systems.
- Water electrolysis using solid polymer electrolytes.
- Hydrogen liquefaction technology.
- Storage/transportation technology for liquid hydrogen.
- Hydrogen storage technology in metal hydrides.
- Hydrogen combustion turbine technology.

Beginning in 1999, Phase Two of WE-NET focused on the utilisation of hydrogen not only from clean renewable energy but on the potential of fossil fuels for near-term introduction of hydrogen energy into the economy. Specific projects included:

- Hydrogen vehicle system component technology related to metal hydride tank systems.
- Hydrogen refuelling station.
- Hydrogen storage materials for vehicle and stationary tank.
- Hydrogen-fuelled solid polymer electrolyte membrane fuel cell.
- Hydrogen-fuelled diesel engine.

The ten-year program benefited from total funding of €18 billion and yielded early achievements including:

- Hydrogen production: Development of a PEM electrolyser with an efficiency rating of greater than 90%, and the development of high performance cell technologies.
- Transportation and storage: Obtained data of thermal conductivity for insulation panels and LH_2 pumps.
- Metal hydride: Developed 2.6 wt% at < 100°C.
- Cryogenic materials: Established data on properties of weld and base metals in LH_2.
- Hydrogen diesel engine: Tested a 100 kW single cylinder engine.
- Hydrogen fuel cells: Developed a 30 kW PEM FC power plant.
- FC vehicles fuel tank systems: Conducted safety test of MH fuel tanks and quick refuelling test for MH tanks.
- Hydrogen filling station: Developed three H_2 filling stations (PEM electrolysis, natural gas reforming and by-product hydrogen system).

The second phase in WE-NET was completed one year ahead of schedule in 2002, and was succeeded by a new project "Development of basic technologies for the safe use of H_2", which started in 2003 (see above).

Fuel Cell industry

Stationary Fuel Cells

- Ishikawajima-Harima Heavy Industries Co.
- Ebara-Ballard Co.
- Sanyo Electric Co.
- Nippon Oil Co.
- Toshiba International Fuel Cell Co.
- Toyota Motor Co.
- Hitachi Home and Life Solution Co.
- Matsushita Electric Co.
- Mitsubishi Heavy Industry Co.

Fuel Cell Vehicles

- Toyota
- Honda.
- Nissan.
- Daihatsu (compact Move).
- Toyota/Hino (Bus).
- Mitsubishi Motor.
- Suzuki.
- Mazda (Hydrogen Rotary Engine).

Korea

- *"21st Century Frontier Hydrogen R&D Program," established in September 2003.*
- *MCFC is the major focus of fuel cell R&D, accounting for 50% of the funding.*
- *Strong leadership from government Ministry of Science and Technology (MOST) and Ministry of Commerce, Industry and Energy (MOCIE); strong participation by world class industry players.*
- *The governmental budget, not including funding from private sector, is expected to be almost US$586 million from 2004 to 2011.*
- *Targets for 2012:*
  - *Development of an efficient prototype hydrogen production system, utilising water-splitting technologies (photocatalytic/thermochemical, and renewable sources.*
  - *Introduce a stationary fuel cell (370 MW) into the market.*
  - *10,000 fuel cell vehicles in operation.*

Overview

Most hydrogen programs in Korea are still at an early, exploratory research stage. Korea's work on hydrogen began in 1988 as part of the larger national R&D program – the "10 year Alternative Energy Technology Development Program." Efforts were relatively minor until 2000, when the Ministry of Science and Technology (MOST) initiated the "High-Efficient Hydrogen Production Program," which formed the foundation of Korea's current program: "21st Century Frontier Hydrogen R&D Program," established in September 2003. Work under this program will be funded by MOST at the level of US$90 million over 10 years from 2003 to 2012. The program is to be the cornerstone for the development of hydrogen technology in Korea. A fundamental technology development program for PEMFC, SOFC, DMFC and next generation fuel cells has also been initiated. It is aimed at eliminating barriers to the commercialisation of fuel cell such as lifetime, reliability and cost. The budget for this fuel cell programme is US$40 million from 2004 to 2011.

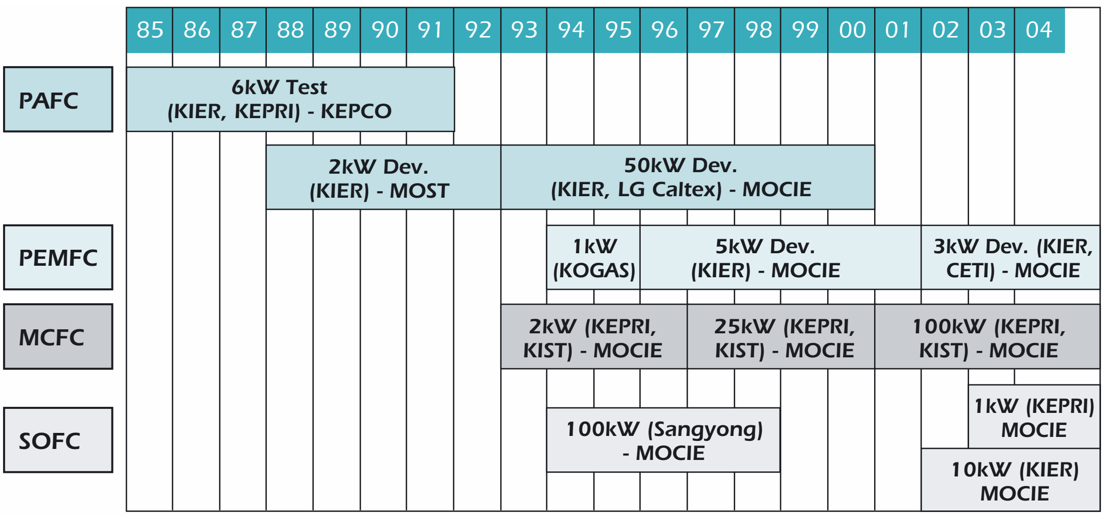
In harmony with this program, a new hydrogen program under the National RD&D Organisation for Hydrogen and Fuel Cell, a subsidiary to Ministry of Commerce, Industry and Energy (MOCIE), was initiated in 2004. The program is to achieve the dissemination target set by MOCIE through demonstrations, such as a hydrogen refuelling station. The budget for this hydrogen program is US$94 million from 2004 to 2011.

With respect to fuel cells, fuel cell technology has been selected as one of the most important and promising technologies, requiring the Korean Government's full support since 1990. The total R&D budget for fuel cell technology invested during the period of 1990-2003 has been approximately US$70 million, spread over 42 projects. Work has been conducted primarily on MCFC, PAFC, SOFC, PEM, with MCFC as the major focus and accounting for 50% of the funding. However, the emerging technologies (PEM, SOFC, DMFC) are recently gaining more importance and government support.

The overall status in Korea is largely still at the R&D stage, but a series of demonstrations of domestic technologies will be scheduled from late 2004. Finally, the Korean Government decided to make a serious commitment to fuel cell development by selecting fuel cells as one of ten economic growth engines. The governmental budget, not including funding from private sector, is expected to be almost US$586 million from 2004 to 2011.

Figure 9

Achievements of Fuel Cell Technologies



Current Status in Hydrogen and Fuel Cell

Type	Status
Hydrogen	Basic technology focused on alternative energy Hydrogen station on LNG, Naphtha
PAFC	Demonstration of 50 kW class system
MCFC	100 kW demonstration plant under construction (2004) 250 kW module development (2008)
Stationary PEMFC	Proto-type 3 kW system development (2004)
Transportation PEMFC	Hybrid (Ni-MH + fuel cell) FCV (2002) FCV (75 kW fuel cell) demonstration (2002)
DMFC	200 W portable power pack development Market introduction for replacement of battery (2006)
SOFC	1.5 kW RPG system (2005) 100 kW SOFC + gas turbine hybrid system

Priorities and targets

A National RD&D organisation for Hydrogen and Fuel Cell was established in December 2003 by MOCIE for expediting the commercialisation of hydrogen and fuel cell technologies. It will not only develop a national plan and strategies, but will also co-ordinate national projects by controlling governmental funds. In terms of hydrogen production, the target for 2012 is the development of an efficient prototype hydrogen production system, utilizing water-splitting technologies (photocatalytic/thermochemical, and renewable sources. Another target is the development of high-purity hydrogen production/supply system utilising fossil fuels such as natural gas, LPG, /methanol, naphtha, etc.

In terms of hydrogen storage, the target for 2012 is the development of a high-pressure gas-storage cylinder (700 bar) and also cryogenic technology to store liquefied hydrogen.

With respect to fuel cells, Korea is working to build up highly competitive capabilities for manufacturing advanced fuel cell technology. The target for 2012 is to introduce stationary fuel cells (370 MW) into the market. In addition, 10,000 fuel cell vehicles are planned to be running on the road by 2012. Small fuel cells for replacing batteries, either DMFC or PEMFC with a micro fuel processor, are expected to be introduced into the market by private companies in 2006.

Korea also plans to introduce new regulations recommending that new buildings owned by the public sector utilise renewable energy technologies like PV and fuel cells from 2004. The government is also planning to establish a coordination committee composed of all stakeholders (public, private, academia) as members. The national strategy will determine the R&D portfolio best suitable to the economy and also other administrative/financial matters necessary for early introduction of a hydrogen economy. Codes and standards, safety, education and market introduction policies and measures will emerge as key issues in the near future.

Program activities

The 21st Century Frontier Hydrogen R&D Program was established in September 2003, and work under this program will be funded by MOST at the level of US$90 million over 10 years from 2003 to 2012. The program is to be the cornerstone for the development of hydrogen technology in Korea. The Program by the National RD&D Organisation for Hydrogen and Fuel Cell was established in January 2004. Work under this program will be funded by MOCIE at the level of US$400 million dollars over 8 years from 2004. This program is to expedite the commercialisation of hydrogen and fuel cell technology. Specific projects include:

- Development of hydrogen production processes, including basic research of hydrogen storage and utilisation.
- Development of hydrogen production technology from water splitting.
- Hydrogen production from natural gas.
- 100 kW MCFC System Development. Industrial participants include: KEPRI, Hyosung Heavy Industries, and Samsung Engineering.
- 100 W DMFC System Development. Industrial participants include: LG Chemical, and LG Electronics.
- Installation and testing of proto-type 50 kW PAFC Systems. Industrial participants include: LG Caltex.

- 3 kW PEMFC for Residential Purposes. Industrial participants include: CETI, LG Chemical Co, Kukdong Towngas Co, KOGAS Corp, and KEPRI.

Budget

The total R&D budget for hydrogen technology until 2002 amounts approximately to US$10 million. The total R&D budget for fuel cell technology invested during the period of 1990-2003 has been approximately US$70 million. However, the budget for hydrogen and fuel cell has been significantly increased. Currently, and not including funding from private sector, is expected to be almost US$586 million from 2004 to 2011.

Key players

Most of energy technologies in Korea are supported by two Ministries – MOCIE (Ministry of Commerce, Industry and Energy) and MOST (Ministry of Science and Technology). MOCIE is more engaged in the development of technologies, which could be applicable or commercialised in short and medium term. MOST is more oriented towards the development of fundamental, basic technologies from the long-term perspective.

- Ministry of Science and Technology (MOST).
- Ministry of Commerce, Industry and Energy (MOCIE).
- The 21st Century Hydrogen R&D Centre: a subsidiary to MOST.
- The National RD&D Organisation for Hydrogen and Fuel Cell: a subsidiary to MOCIE.
- Korea Institute of Energy Research.
- Korea Institute of Science and Technology.

Government policy

Several subsidy programs are managed by the Korean Government to facilitate the market introduction of hydrogen and fuel cell product. These include: (a) the mandatory installation of new and renewable energy technology in new buildings owned by the public sector, such as PV and fuel, from 2004. It is expected that at least 5% of total construction cost should be used for NRSE installation; (b) the promotion of fuel cell dissemination by subsidising the difference between the electricity generation cost and the market price of electricity. This initiative will come into force from 2006.

The Korean fuel cells industry

21 private companies and 3 public research institutes are actively involved in its research and development.

Hydrogen

- KOGAS: Production.
- SK: Production.

- LG-Caltex: Production.
- NGVTEK: Internal combustion engine.

Fuel Cells

- Electric Power Generation: distributed or larger capacity:
  - KEPCO (Korea Electric Power Company)/KEPRI.
  - POSCO/RIST.
  - Doosan Heavy Industry.
  - Samsung Engineering.
  - Hyosung Heavy Industry.
  - LG-Caltex.
  - Twin Energy, AutoEn.
- Transportation:
  - Hyundai Motor Company.
  - SK.
  - Mobis.
  - NGV.
  - Heesung-Engelhard.
- RPG:
  - LG-Caltex/CETI.
  - Samsung SDI.
  - LG Electronics.
  - FCP.
  - KOGAS.
  - Kukdong Towngas.
  - Hankook Tire.
  - KEPRI.
- Mobile application:
  - Samsung SDI/S.A.I.T (Samsung Advanced Institute of Technology).
  - LG Chemical.
  - SKC.
  - Hyupjin.

Other activities

Korea Atomic Energy Research Institute will launch the project of the development of HTGR (High Temperature Gas cooled Reactor) for hydrogen production by March 2004.

Netherlands

- *Priorities are driven by environmental concerns and experience with natural gas, including the existing natural gas infrastructure.*
- *Intensive R&D is underway on the production of hydrogen from natural gas and biomass.*
- *Demonstration highlight: The world's largest SOFC system, a 100 kW Siemens-Westinghouse SOFC installed at a Dutch cogeneration plant in 1998.*

Overview

The publicly-funded fuel cell research program started in 1985, with the main activities performed at the Energy research Centre of the Netherlands (ECN). Between 1985 and 2001, about €100 million was invested by mixed public-private funds in the development of fuel cell and hydrogen energy. The objectives of the Dutch fuel cell programs were initially oriented to the application of coal gas in MCFC based systems. The MCFC activities were terminated in 2001, after an evaluation failed to indicate its commercial viability with natural gas. Afterwards, the activities shifted to SOFC and PEM technology for high efficient conversion of natural gas in small-scale decentralised units.

Research on SOFCs started in 1990 for CHP applications and in 1992, PEM activities started to focus on CHP, traction and portable applications. Both types of systems are being actively pursued along with early demonstrations. Additionally, the use of fuel cells and bio-gas or biohydrogen is being evaluated.

The Netherlands' intensive experience with natural gas technology is also prompting work on the possible introduction of hydrogen in the natural gas grid, which could enable substantial amounts of hydrogen to be introduced in the marketplace. In addition to R&D institutes, the Dutch energy industry has become involved in hydrogen work, including Shell-Hydrogen and Gasunie. These companies perform their own research and participate in multiple EU co-funded and other international projects.

In 2003, the "Hydrogen Networking" program was initiated, with the objective to stimulate National and international co-operation and programmatic tuning. In addition, the public-private funded "Sustainable Hydrogen" program has been initiated. Its objective is to stimulate hydrogen research activities in the academia.

Priorities and targets

Current activities are performed in multiple programs. Priorities are related to the existing natural gas infrastructure and are guided by environmental concerns, in line with the objectives of the Kyoto Protocol, and in close contact with intensive international structures on co-operative R&D and information exchange. Accordingly, sustainable hydrogen became an issue, in parallel to other sustainable energy carriers. These days, most hydrogen and fuel cell activities are being stimulated

through parallel, generic energy programs. These, mainly generic programs, aim at the clean and sustainable use of natural gas (including CO_2 capture and sequestration) and the use of renewable sources.

The Ministry of Economic Affairs has created three governmental projects supporting the process of the changes to be made in the energy-infrastructure. These projects are called:

- Transition Management;
- Clean Fossil Energy;
- New Gas.

The activities assist in the identification of: stakeholders, public aspects, energy concepts, technologies, non-technological issues and road-map type of actions.

Program activities

- **General R&D on hydrogen.** All aspects on hydrogen R&D are being explored at various universities and institutes and in the private sector. Work includes: hydrogen production, handling, storage, infrastructure, and its applications (including fuel cells). Non-technical programmes for public awareness, normalization, safety, and codes and standards are also being pursued.
- **Hydrogen from biomass.** There are a number of biological projects for manufacturing Biohydrogen, and there are various thermal and hydro-thermal processes being developed.
- **Policy Studies on infrastructure** considerations and transition management activities include: (a) Fuel Cell RD&D activities; (b) SOFC and PEMFC cells, stacks, systems are being developed in relation to local generation; (c) Systems field testing is being undertaken by Siemens-Westinghouse, Sulzer, and Plug-Power.

Budget

The hydrogen and fuel cells projects are funded by a mix of public and private sources and through tax incentives. The estimated annual budget is over €30 million, which includes about €8-10 million in public funding.

Notable activities

- **Hydrogen production.** Intensive R&D is underway on the production of hydrogen from natural gas and biomass. Concerning biological hydrogen, a national co-operative platform has been formed with 11 institutes and universities. In addition, thermal (pyrolysis) and hydrothermal processes are being studied at multiple places. Other research areas include various thermal and hydrothermal processes (BTG, TNO, ECN), and hydrogen from electricity produce by renewables (solar, wind, and tidal power).
- **Fieldtesting 100 kWe SOFC system (Siemens-Westinghouse).** The 100 kW SOFC CHP test unit was installed at a Dutch cogeneration plant in 1998, as one of several units to be tested in the joint government-industry development effort. The test is being carried out at the local utility in Westervoort by NUON, which operates the system for EDB/Elsam. Funding for the

test is also being provided by the Dutch government agency Novem. The test unit is the world's largest SOFC system, and has operated for a record 8,760 hours. The unit fuel-to-electricity efficiency reached 46 percent. It supplied 110 kilowatts of electricity to the local power grid – better than its "nameplate" capacity – along with hot water to the area's district heating system. Emissions of nitrogen oxides were below 0.2 parts per million, well within the most stringent of air quality standards. Sulphur oxides, carbon monoxide and volatile hydrocarbons were all measured at less than 1 part per million. The test phase in the Netherlands has been completed; the system has been transported to Germany where it is undergoing an additional test phase.

- R&D on SOFC and PEM, stacks and systems: in relation to local generation, CHP and u-CHP on the basis of natural gas and hydrogen in the future (ECN, NedStack, Hexion).
- International programs. The Netherlands participates in a number of international and EU-sponsored programmes, including:
  - CUTE – EC bus project (Amsterdam public transportation, Shell, Hoek-Loos).
  - EIHP – European codes & standards (Shell).
  - NaturalHy – H_2 mixtures in natural gas (Gasunie).
  - Fresco Hydrogen-Fuel cell Scooter project (ECN).
  - Virtual powerplant EU Fieldtesting project of over 30 PEM systems (GasUnie, Vaillant, Plug Power NL).
  - HyNet EC co-funded network project (Industry oriented: Shell-Hydrogen).
  - HyWays EC co-funded (European Road Maps: Shell-Hydrogen, Novem, ECN).
  - Fuel Cell system evaluations SOFC and SPFC u-CHP systems by utilities (Siemens-Westinghouse, Sulzer, Plug-Power).
  - Green-Gas project, to prepare for technology to apply natural-hydrogen mixtures as structural energy carrier.

Key players

- Ministries of Economic Affairs; Housing, Spatial Planning and Environment; Transportation.
- Shell: Fuel processing, Refuelling, Traction (GVB: CUTE).
- Gasunie: R&D, EU Virtual power plant and "Green Gas" (NaturalHy).
- Utilities: fieldtests FC-u CHP.
- Innovative SME's: BTG, Sparqle, Plug-Power, NedStack, Hexion.
- Institutes: ECN, TNO: R&D, production, components, modelling, systems, strategic infra-structural studies.
- Universities: Twente, Delft, Wageningen, Amsterdam, Leiden, Utrecht, Eindhoven: fundamental and applied research.

New Zealand

New Zealand has one major hydrogen project underway. Launched by CRL Energy Limited and Industrial Research Limited in July 2002, the project aims to demonstrate electricity production from New Zealand coal by the development of an integrated gasification, syn-gas clean up, fuel cell package. The New Zealand Government, through the Foundation for Research Science and Technology, is funding the six-year project. The overall goal is to create the technological platform and expertise required to allow New Zealand to realise the benefits of moving to a hydrogen-based energy economy. The project completion date is July 2008.

There is also a coal gasification unit under development. It is an atmospheric, air-blown fluidised bed pilot gasification plant. It is planned to convert this to an oxygen blown system once the initial commissioning of the plant is complete. Industrial Research Limited is developing one of their alkaline fuel cell systems for use in the project. As alkaline fuel cells require very high purity hydrogen for use as a fuel, the separation of high purity hydrogen from the gasification syngas is critical.

There are three technical centres involved in Hydrogen research:

- CRL Energy Limited.
- Industrial Research Limited.
- Unitec Institute of Technology.

Norway

- *Significant efforts focusing on CO_2 sequestration in the North Sea.*
- *National priority to investigate hydrogen production from abundant, domestic natural gas resources.*
- *Active participant in a number of EU Framework projects and several international demonstration projects.*

Overview

The hydrogen and fuel cell related activities in Norway have mostly been parts of larger R&D programs within the field of renewable sources of energy. With respect to fuel cells, in 1990 some government-funded research work was conducted on SOFCs, however a major part of this activity has been discontinued. More recently, there have been a few projects on fuel cell activities funded through other energy research programs.

The main effort during the last 5-10 years has been on fundamental and basic R&D related to material sciences, membranes for fuel cells, catalysts for PEM-fuel cells, electrolyses, and materials for hydrogen storages (mostly hydrides).

With Norway's significant natural gas resources, hydrogen production from natural gas with CO_2 capture and storage is now a high priority in Norway. In addition to natural gas resources, Norway has access to huge areas suitable for CO_2 sequestration in the North Sea – estimated to have the capacity of storing all CO_2 from power production in the whole western Europe for at 600 years. The possibility of using CO_2 in enhanced oil recovery also holds great promise for oil production, and a project on the oil field "Gullfaks" is under consideration. Besides natural gas, the Norwegian company Norsk Hydro is one of world's leading producers of electrolysers, with a strong competency in electrolysis technology that has been built up over many years.

The Norwegian national hydrogen commission identified hydrogen production from abundant, domestic natural gas resources as a key priority.

Priorities and targets

The Government established a national Hydrogen Commission to define national targets to develop hydrogen as energy carrier, identify means and instruments for added value and better environment, identify necessary participation from government and framework conditions, and propose organisation and necessary funding for a national hydrogen program. The Commission delivered their report to the Minister of Petroleum and Energy and the Minister of Transport in June 2004. The commission report identifies four target areas for a national hydrogen initiative:

- Environmentally-friendly production of hydrogen from Norwegian natural gas.
- Promote the early user of hydrogen.

- Improve hydrogen storage.
- Develop a hydrogen industry.

The Commission proposes a 10-year programme focusing on R&D and demonstration, with an overall budget of €120 million over the period. The priorities for research activities, managed by the Research Council, will be adjusted after the commissions report has been evaluated by the Government.

Program activities

Project Overview

- Hydrogen Production (6 projects).
- Hydrogen Storage (5 projects).
- System Analysis (5 projects).
- Fuel Cells (2 projects).
- Hydrogen related projects within CO_2-sequestration (3 projects).

Specific Project Activities

- **Research program RENERGI.** An overall energy technology development program with a hydrogen and FC research element. The funding for the hydrogen and FC research element is approx. €200,000 annually.
- **Energy for the future.** Basic research and education of PhD students. €1 million.
- **The Utsira project.** Utsira is a small community on an island, isolated from the electricity grid and thus making it possible to demonstrate an autonomous energy system. The project consists of using a wind turbine to produce electricity. The production not directly used will be used for producing hydrogen by water electrolysis. The hydrogen is then stored and used as backup for producing electricity from a hydrogen combustion engine and an fuel cell when there is no wind. The installation commenced in January 2004 with €1.7 million in public funding. Total cost is approx €5 million.
- **Hydrogen for gasification.** Studies on integrated SOFC and biomass gasification. The overall objective is to identify a process to gasify biomass and receive hydrogen with a purity sufficient for SOFC using a sandfilter.
- Photobiological production of hydrogen.
- **Chemical/Metal hydrides.** This is an important area in Norway and there is a substantial effort being put into five different projects with different approaches related to using metal hydrides.
- **Carbon nano-tubes.** This is a postdoctoral project at the Institute for Energy Technology and the Physics institute.
- **Safety, Codes and Standards.** There are five projects covering different aspects of system challenges when integrating hydrogen technology into an energy system. Important objectives are safety, codes and standards, dynamic behaviour of fuel cell systems, and the evaluation of demonstration projects.
- **Electrochemistry.** Major focus on material science related to membranes/proton conductors. Topics include hydrogen separation membranes, proton conductors, and fast oxygen and proton conductors.

- **PEM.** The effort on PEM is mostly at the NTNU in Trondheim. The activity presently concentrates on two projects. The major objectives are two-fold: develop alternative catalysts or processes reducing the use of platinum as a catalyst; and fundamental research on reversible PEM/electrolyser.
- **SOFC.** One SOFC project is to open up for offshore production of oil and gas without CO_2 emissions to the atmosphere. Another activity is concentrated on improving the working efficiency and competitiveness of SOFC fuel cells for power generation with natural gas. The third R&D activity on SOFC is related to filter mechanisms for cleaning hydrogen from gasified biomass to reach sufficient purity for use in an SOFC.

International activities

Projects from the 5th EU Framework:

- HyNet.
- HySociety.
- Renewable Islands.
- EIHP.
- Renewable Hydro.
- CUTE – Demonstration of H_2 fuel cell buses.

Projects from the 6th EU Framework:

- Hyways.
- HySafe.
- StoreHy.
- NATURALHY.
- New-H-Ship.

Norway is a member of the ISO/TC-197 group, developing standards for hydrogen systems.

International Demonstration Projects

INE – Icelandic New Enrgy and ECTOS.

CUTE – demonstration of 27 hydrogen fuel cell buses in 9 cities.

CEP Berlin – Clean Energy Partnership.

HYNOR – hydrogen for transportation in Norway.

Budget

Total project funding to date has been reported as follows:

- Fuel Cells: €0.5 million.
- Production of hydrogen: €3.3 million.
- Hydrogen storage: €3.4 million.
- Hydrogen systems analysis: €2 million.

Portugal

- ***Hydrogen strategy is to focus on technological development for decentralised and distributed energy systems.***
- ***Programme leadership from the INETI National Institute.***

Overview

In Portugal, there is no specific national programme on either hydrogen or fuel cells, however, there are ongoing activities both on hydrogen production and storage and fuel cell R&D in universities and research centres, some in close cooperation with industry. One the main issues of the New Energy Vectors of the strategic plan of the INETI National Institute, where more than 85% of the national non-nuclear energy budget is allocated, is hydrogen production through renewable energies, reforming of natural gas, and gasification of coal and biomass. Some work is also done on the utilisation of hydrogen in fuel cells both for fixed and mobile applications. Another area of development is the production/storage of hydrogen using chemical/metal hydrides.

Priorities and targets

The hydrogen strategy is to focus on technological development for decentralised and distributed energy systems, strengthening international cooperation within EU and IEA, and promoting industrial competitiveness.

Projects and activities

- **Project PRO-H_2.** In this project, a low temperature hydrogen producing process is studied using chemical hydrides (binary and complex) as producing agents with high volumetric efficiency, able to compete with available storage options such as compression and liquefaction. The project involves: the production of hydrogen from binary and complex hydrides; synthesis and characterization of suitable catalyst; study of reaction kinetics; reactor project and construction; and, potential recycling of reaction products. The project has participation from INETI, IST, INEGI and SRE and is funded at €981,000.
- **PROTAP.** The project, financed by the National/EU Programme PEDIPII, is aimed at the implementation of an infrastruture for the research and demonstration of low temperature PEMs and new materials for components and testing of operating conditions.
- **Catalytic Activity of Cathodic Materials for MCFCs.** This project, supported by the Programme for Scientific and Technical Bilateral Cooperation between Portugal and Spain), addressed stability of materials and the electrolyte under operating conditions and consequent loss of catalytic activity. Given the complexity of the problem and the time context for this type of project, the research was limited to the cathode: Dissolution of LiNiO cathodes has lead to the search for novel alternative materials that, exhibiting high electronic conductivity and

catalytic activity for the oxygen evolution reaction, were also thermodynamically stable in molten carbonate.

- **Transport Phenomena in Direct Methanol Fuel Cells. Modelling and Experimental Studies.** The project is aimed at the development of a DMFC model comprising the mass transport of the gases in the diffusion layers and catalysts layers, mass transport in the membrane and the potential distribution in the catalysts layers. The model will be experimentally validated in a DMFC constructed during the project development. This project to be financed by the Portuguese Foundation of Science and Technology involves a University (FEUP) and a State Laboratory (INETI). Associated Budget: €35,000.
- **EDEN: Endogenising the Use of New Energies.** This demonstration project is aimed at creating a technological platform, at a national level, able to intervene in the mutation process of the actual energetic paradigm to a new one, in which hydrogen will play a very important role, developing solutions for the production of decentralised energy using fuel cells. Participants: INETI, INEGI, IST, CPPE, EFACEC, AUTOSIL Proposed Budget: €8,323,230.
- **Membrane Fuel Cells for Application in the Transport Sector.** Project developed by INETI, aiming at securing a scientific and technological base necessary for the implementation of the study of membrane fuel cells for transportation. Associated budget: €420,000.
- **Gasification of biomass and waste and Co-gasification.** Technology development by INETI based on fluidised bed technique, producing gas with up to 65% oh hydrogen, aiming at demonstrating the viability for power production using SOFC. Associated budget: €1,200,000.

International activities

Portugal participates in a few networks under EU programmes, namely:

- CO_2Net.
- Powerclean.
- Hy Society.
- FCTESTNET.

Spain

- ***Spanish industries participate in numerous EU-sponsored hydrogen and fuel cell projects.***
- ***Hydrogen refuelling stations in Madrid and Barcelona.***
- ***Significant participation by public research institutions and technology centres.***
- ***Investment from Spanish private companies, research and technological centres and universities for the period 2001-2005 has been approximately €50 million.***

Overview

Spain initiated activities in hydrogen and fuel cells research in the early 1990s, and continues to focus its work in the areas of hydrogen production (from renewable and fossil sources), hydrogen storage (research focused on nanotubes and metallic hydrides), the development of components for MCFC and PEMFC and SOFC, fuel cell design, and fuel cell testing for AFC, PEMFC, PAFC and MCFC stacks and components. Spanish industries have also taken part as partners in hydrogen and fuel cell European projects. At the present time this participation is being increased and the responsibility is growing as Spanish Research Centres and companies are playing the role of coordinators in some European projects.

Regarding industry funding in the past, the most relevant contributions have been the development, construction and operation of a 100 kW MCFC stack; and an industrial hydrogen production plant based in the utilisation of coal in IGCC (Integrated Gasification Combined Cycle) format, owned by ELCOGAS and sited in Puertollano (Central Spain). In addition, IZAR has experience operating a 250 kW MCFC stack (since November 2002) supplying electricity and heat for its motor factory in the South of Spain.

The level of involvement of Spanish car industries is also increasing, as well as other industries as industrial gases, utilities and renewals. Spain participates actively in transport demonstrations with seven hydrogen buses running in Madrid and Barcelona, where there are two of the first hydrogen refuelling stations in Europe.

Priorities and targets

The following areas have been identified as priorities for realising the potential of hydrogen and fuel cells:

- Production: The focus is on hydrogen production without CO_2 emissions from water, employing electrolytic methods (with renewable energy or nuclear) or another emerging technology, such as photoelectrolysis, photobiology or biomimetic processes. Spain is also interested in producing hydrogen from fossil fuels, with CO_2 sequestration.
- Storage: Compressed, liquid or trough metallic hydrides and nanotubes carbon structures.

- Distribution and final supply: Utilisation of existent and new infrastructures, distribution methods and end supply installations.
- Standards and specifications for equipment, safety and product quality.
- Putting into operation pilot and demonstration installations of integrated systems based in hydrogen.
- Development of other fuels for feeding fuel cells (natural gas, methanol, bioalcohols, oil fractions etc.) relative to profitable and clean production, purification and infrastructure development.
- With regard to low temperature fuel cells (PEM), efforts must be guided to materials development (catalysts, electrodes, electrolytes, plates, seals, etc), fuel cells components development and its manufacturing methods, fuel cells prototypes development, systems based in fuel cells for transport, stationary and portable applications, and fuel processors.
- High temperature fuel cells (solid oxide and molten carbonates): efforts must be guided to materials development (catalysts, electrodes, electrolytes, plates, seals, etc), fuel cells components development and its manufacturing methods and fuel cells prototypes development.

Program activities

- Design and demonstration of safety and competitive use of residual hydrogen for combined cycle energetic optimisation. The goals are to achieve 70% energy efficiency in a natural gas combined cycle by supplying residual hydrogen from propane dehydrogenation (to produce propylene) to the recovering boiler.
- Development and construction of an HFC urban bus for Madrid. The main objective is the demonstration of the technical and economic viability of an advanced fuel cell propulsion system combined with innovative vehicle concepts for public transport application. This work was done in combination with the ES H_2 Hydrogen refuelling Station in Madrid.
- H_2 Refuelling station in Barcelona. Electrolysis production of hydrogen, which will be supplied at high pressure to three buses participating in the European CUTE project. It will be the first hydrogen production plant with a solar photovoltaic system, producing 10% of electricity needs.
- Mini Electricity Generation with SOFC. Development of 1 to 2 kW SOFC for application in distributed generation. The process for hydrogen production is natural gas steam reforming.
- R&D for hydrogen production for its utilization in fuel cells, based in Syngas obtained through gasification process.
- Fuel Cells for Defence Application. This R&D Fuel Cell Program for defence applications has the main objective of analyzing current fuel cells and reformers and promoting their integration in mobile and stationary defence applications. Work will include and diesel and ethanol reformers.
- PEM 500. Research, development and manufacturing of 500 W PEMFC.
- TELEPEM. Design and validation of experimental PEMs up to 1 kW for telecommunications.
- EXPERT AUTOTHERM. Development of 75 kW methanol reformer for working with 75 kW PEMs integrated in automobile vehicle.
- COPICO-GAS. Development of a domestic cogeneration system based on the use of a PEM using natural gas as input fuel (PEMFC).
- Technology development of a 5 kW PEM, integrated with a reversible heat pump and photovoltaic field.

- BIOPLASMA. Development of bioethanol to hydrogen conversion reactor through low temperature plasma.
- BIOCELL. Bioethanol utilization as fuel for fuel cells.
- Research, development and exploitation of SOFC.
- Development of hydrogen production via electrolysis from electricity generated by wind energy.
- Biohydrogen. Hydrogen production by fermentation using wastes.
- Development of a 50 WtDMFC for portable applications.
- Hydrogen storage by adsorption in nanotubes and molecular sieves.
- PILEREN. Demonstration project on PEM utilization in the residential sector.
- New solid electrolytes with high electric conductivity from polymeric nanofoams.
- Development of new methods for catalysts application over electrodes for fuel cells.
- Nanotechnology and its application to hydrogen storage.

International cooperation

Spain is active in a number of European and international projects, including:

- RESH2 – Cluster Pilot Project for the Integration of RES into European Energy Sectors using Hydrogen.
- DICCOM – Production of power and heat with 250 kW MCFC for utilization in a motor factory.
- FIRST – FC Innovative Remote system for Telecom.
- CUTE – Clean Urban Transport for Europe.
- CEXICELL – Development of Cost Effective and High Quality Planar Solid Oxide Fuel cells by Using Advanced Thermal Spray Techniques.
- MIGREYD – Modular IGCC concepts for in-refinery energy and hydrogen Supply.
- EFFECTIVE – Holistic integration of MCFC technology towards a most effective systems compound using Biogas as a renewable source of energy.
- SIDMT – Metal Hydrides Manufacturing.
- European Integrated Hydrogen Project – Phase II.EIHP2. Provide inputs for regulatory activities on a EU and global level to facilitate harmonised procedures for the approval of hydrogen fuelled road vehicles, hydrogen refuelling infrastructure, and the relevant interfaces between the vehicle and the filling station.
- FEBUSS – Fuel Cell Energy Systems Standardized for Large Transport, Buses and Stationary Applications.
- HY Society.
- FCTESTNET.
- HyNet.
- Advanced PEM Fuel Cells. APOLLON.
- AMONCO – Advanced prediction, monitoring and controlling of anaerobic digestion processes towards biogas usage in fuel cells.

- Construction of 100 kW MCFC Plant located in San Agustín de Guadalix (near Madrid), with the participation of Ansaldo, ENEA and ITAE in Italy and the Spanish partners Iberdrola, Endesa and Babcock & Wilcox. This test facility is unique in Europe.
- Development of 1 kW reformed methanol fuel cell, carried out by CIEMAT, CSIC and SEAT in Spain with the participation of KTH (Sweden) and UTAD (Portugal).

Budget

Investment from Spanish private companies, research and technological centres and universities for the period 2001-2005 has been approximately €50 million.

Key players

Three specific associations for hydrogen and fuel cells have been established: the Spanish Hydrogen Association, the High Council for Scientific Research Fuel Cells Network and the Spanish Association for Fuel Cells.

Public research institutions and technology centres

- CIEMAT: Research Centre for Energy, Environment & Technology (*www.ciemat.es*).
- IAI-CSIC: Institute for Industrial Automatics (*www.iai.csic.es*).
- ICP-CSIC: Institute for Catalysis and Petrochemistry (*www.icp.csic.es*).
- ICV-CSIC: Institute for Ceramics and Glass (*www.icv.csic.es*).
- ICTP-CSIC: Institute for Polymers Science and Technology (*www.ictp.csic.es*).
- INTA: National Institute for Aerospace Technology (*www.inta.es*).
- CARTIF: Centre for Automatics, Robotics, Information Technology and Manufacturing (*www.cartif.es*).
- CIDAUT: Centre for Automobile R&D (*www.cidaut.es*).
- CIDETEC: Centre for Technological Research in Electrochemistry (*www.cidetec.es*).
- IKERLAN: Basque Foundation for Development of Energetic Technologies (*www.ikerlan.es*).
- INASMET: (*www.inasmet.com*).
- ITC/ITER: Technological Institute of Canary Islands (*www.itccanarias.org*).

Industry

- EADS, CASE, SENER.
- AJUSA, ATIPIC, Expert, Iveco/Irisbus, Seat.
- Aben-Goa, Aries, Empresarios Agrupados, Lonjas.
- Abello-Linde, Air-liquides Spain, Praxair Spain, Carburos-Air Products.
- Elcogas, Endesa, Iberdrola.
- Gas Natural, Gas de Euskadi.
- BP Spain, Cepsa, Repsol YPF.
- EHN, Eolica de Navarra, ISO-Foton.

Sweden

- ***Government activity has been in cooperation with the electric power and automobile industries.***
- ***Consortium for Artificial Photosynthesis between several Swedish Universities focuses on basic R&D on artificial photosynthesis using the sunlight directly to produce hydrogen from water.***

Overview

The Swedish National Energy Agency is the main governmental actor for both hydrogen and fuel cell work. Although a number of initiatives have been taken by both the public and private sectors, there is no national program or strategy for hydrogen related activities existing in Sweden today. Nevertheless, the Swedish National Energy Agency has pointed out hydrogen and fuel cells as one of the strategically important areas for the future and has begun to fund various projects. The overall budget is approximately €4 million and a large part of the funding has been for specific projects related to PEM fuel cells in the transport area.

Energy utilities have also been involved in Swedish HFC work. Notably, the Swedish energy company Sydkraft has constructed a filling station for hydrogen as well as for a mixture of hydrogen and natural gas. The mixture will be used in buses in Malmö (south Sweden) and aims at demonstrating that hydrogen is already available to the energy sector, although notably still too expensive. The demonstration program will last two years in the first phase.

The only large-scale program is the consortium for artificial photosynthesis between several Swedish Universities. The project is focusing on basic R&D on artificial photosynthesis using the sunlight directly to produce hydrogen from water.

Priorities and targets

The Swedish National Energy Agency has set a 2006 target to reform hydrogen and oxygen from water with sun energy through artificial photosynthesis.

Program activities

- Under the Swedish Consortium for Artificial Photosynthesis, the university of Uppsala (photo biological hydrogen production and photoelectrochemical production of hydrogen), and KTH (storage of hydrogen) are cooperating to develop an educational exchange between students at the different faculties. Since 2003, this program includes photo-biological hydrogen production from cyano bacteria.
- Sweden has several R&D programs related to stationary and transportation fuel cell applications. Much of the government activity has been in cooperation with the automobile industry (Saab

and Volvo), which is highly-knowledgeable of system analysis, components and small-scale niche markets. Examples of successful Swedish experiences in small-scale enterprises are Opcon Autorotor (compressor systems for fuel cells in vehicle) and Catator (small scale reformer for natural gas).

- The ongoing programs related to fuel cells in Sweden include basic research programs which are a part of larger energy research programs on PEM, SOFC, MCFC applications. Research is also being conducted in power systems in vehicles, hybrid vehicles, combustion engines, and "green cars" applications.
- The Alternative Motor Fuels program has its main focus on fuels made by gasification of biomass, but it also includes projects on hydrogen.
- Under the Chrisgas project, biomass will be gasified to produce hydrogen-rich synthesis gas in a pilot plant at Värnamo in the south of Sweden. The project will study the extraction of hydrogen in conjunction with biogas production.

International Cooperation

The Swedish Energy Agency cooperates with several actors nationally. This cooperation includes specific projects addressing various important aspects of technical development such as strategic studies (Energy foresight study); cooperation with a large group of stakeholders in the transport sector; arranging regular conferences about fuel cells and batteries; handling strategic issues of relevance to component suppliers to the vehicle manufacturers. Sweden is engaged in the following IEA implementing agreements related to the transport sector: IEA Hydrogen production and utilisation; IEA Advanced Fuel Cells; IEA Advanced Motor fuels; IEA Hybrid and Electric Vehicles.

Sweden is a participant in the EU demonstration project CUTE (Clean Urban Transport for Europe) where 3 Fuel cell buses are run in each of 9 European cities. The hydrogen, which provides fuel for the FC buses, is produced locally by electrolysis. Sweden has recently joined the Hydrogen and Fuel Cell Technology Platform organised by EU.

Key players

- The University of Lund and the Royal Institute of Technology Stockholm are cooperating to improve knowledge of stationary fuel cells (program funding from the Swedish National Energy Agency). Elforsk, the research organization for the Swedish power producing industry, is coordinating the program.
- Batteries and Fuel Cells for a Better Environment: the Chalmers University of Technology Gothenburg and the Royal Institute of Technology Stockholm are conducting research that is being funded by Mistra, The Foundation for Strategic Environmental Research.
- The energy company Sydkraft, which has constructed a hydrogen refuelling station.
- The Swedish National Energy Agency: *http://www.stem.se/english*

Switzerland

- *Goal is to regionally produce hydrogen by splitting water using hydropower/electrolysis or solar radiation.*
- *Research on SOFC is concentrated at Sulzer Hexis, in close collaboration with the Federal Laboratory for Materials Research and the Federal Institutes of Technology Zurich and Lausanne.*
- *2050 target market penetration for fuel cells to provide 5% of primary energy*

Overview

In the Swiss National Energy Research and Development Programme, hydrogen is considered one of the most important future secondary energy carriers, as well as an economically important chemical commodity. Consequently, the Swiss authorities continue to support activities for the sustainable production, safe storage and efficient use of hydrogen. The latter also includes fuel cells, which may become an important component in future energy conversion systems. Switzerland has been engaged in hydrogen and fuel cell development for roughly 25 years. The work has focused on:

- Hydrogen production. Topics investigated include: (a) high pressure electrolysis of water using Switzerland's extensive hydropower; (b) thermo-chemical splitting of water using a high temperature metal/metal oxide redox cycle driven by concentrated solar radiation: and, (c) room-temperature generation of hydrogen by the photo-catalysed splitting of water using solar radiation via the so-called tandem-cell. In addition, hydrogen production from fossil-fuel sources (de-carbonisation) and from bio-mass have been studied.
- Hydrogen storage. Efforts have been made to identify and test metals and alloys to optimise hydrogen storage capacity and to explore technically feasible charge/discharge characteristics. Analogous efforts were carried out to develop quasi-liquid systems, i.e. suspensions of microscopic metal hydrides in organic solvents. Medium pressure storage of hydrogen from electrolysis in big steel tanks has been successfully demonstrated at Djevahirdjian S.A. Studies are being performed on high pressure storage of gaseous hydrogen in light weight CNG-4 tanks.
- Fuel cells. Topics include both SOFC and PEM type fuel cells. Also R&D for DMFC has been investigated. Emphasis was given to solving problems related to fulfilling the market requirements of the Sulzer Hexis SOFC. The main goal is to increase both reliability, lifetime, and the power conversion rate, while reducing costs. Considerable efforts were also invested in the development and demonstration of the PEM. Outcomes of this work include a 60 kW stack for cars demonstrated successfully in 2002 in the VW Bora and recently in a much improved car. The 1 kW-unit "Power Pac" is a standalone unit'; its PEM-stack has been demonstrated in various applications like boats and small cars (SAM).

Priorities and targets

Switzerland's long-term goal is to regionally produce hydrogen by splitting water using hydropower/electrolysis or solar radiation. Thereby, fossil fuels can be substituted by renewable and efficient hydrogen supply chains. The present and future policy aims at identifying and developing key activities rather than supporting a large spectrum of dispersed projects. The strategy for hydrogen technology focuses on its production using renewable energy and storage and distribution logistics (high pressure technology, fast filling, etc.). Considerable attention is being given to testing and developing novel materials and devices, which will safely and reliably serve different functions along the whole hydrogen supply/production/utilisation chain. Fuel cell activities address SOFC and PEM systems supplied with either natural gas/biogas or hydrogen. For both technologies scientific as well as manufacturing problems are under investigation.

The commercialisation plan for hydrogen:

Start demonstration: present – 2030.

Start market introduction: 2015-2050.

Market penetration 5% of energy use: ~ 2060.

The commercialisation plan for Fuel Cells:

Start Demonstration: now – 2030.

Start Market Introduction: 2005-2050.

Market Penetration: 5% of primary energy transformation by FC.

Key players

Research and development of hydrogen energy and technology are logistically co-ordinated and financially supported by the Swiss Federal Office of Energy. Federal and cantonal research institutes, as well as private institutions and industries guarantee additional financial support. The Swiss Hydrogen Competence Centre, Hydropole, was established in 2000. It centre surveys ongoing pilot and demonstration projects, and documents and promotes new alliances among institutional and industrial partners. All activities are closely co-ordinated with the IEA and EU research programs.

Hydrogen research is carried out in different institutions: solar driven hydrogen production is under investigation at the Paul-Scherrer-Institute, while photocatalytic splitting of water is the focus of work by an alliance of the Universities of Bern and Geneva and the Federal Institute of Technology Lausanne. Hydrogen storage is being explored at the Universities of Fribourg and Geneva (both are focusing on metal hydrides) and at the University of Applied Science in Geneva. The use of hydrogen to produce chemical commodities is under study at the Federal Institute of Technology Zurich; and functional materials are being developed and tested at the Federal Institute for Material Testing. Close collaboration exists with the University of Augsburg.

Research on SOFC is concentrated at Sulzer Hexis, in close collaboration with the Federal Laboratory for Materials Research and the Federal Institutes of Technology Zurich and Lausanne. The industrial lead in SOFC-Technology is Sulzer Hexis. There are new activities in SOFC manufacturing by the

start up company HT-Ceramics, which has developed a specific (anode supported thin layer electrolyte) SOFC system. The PEM research is carried out by the Paul Scherrer Institute in collaboration with the Federal Institute of Technology Zurich and the University of applied science in Biel. The Paul Scherrer Institute is also researching DMFC systems, while the Federal Institute of Technology Lausanne is involved in research activities for HTcceramics.

Budget

In the last 25 years, approximately €100 million has been invested spent by public institutions for hydrogen research. The current annual budget amounts to about €4 million. An additional €3.5 million are invested annually in different hydrogen-related projects in the use of hydrogen as a fuel or chemical commodities, as well as for program management and information activities. The funding for fuel cell R&D adds a further €6 million annually to the budget.

Roughly 25% of the HFC budget is funded by the Swiss Federal Office of Energy, 30% by the Board of the Swiss Federal Institute of Technology, 20% by the Swiss National Foundation and 25% by the Cantonal Universities. Private funding for hydrogen R&D is about €0.75 million per year, while fuel cells receive about €6 million annually.

The Swiss hydrogen and fuel cells industry

Research activities, including novel hydrogen production and storage technologies, are carried out by closely interacting teams from research institutions and industry. Industries like Hrand Djevahirdjian SA, Monthey (production of sapphire and other precious stones, and large scale hydrogen production by a high pressure electrolyser), Pangas AG, Winterthur (hydrogen trader), Linde Cryotech AG, Lucerne (liquefaction of hydrogen), Ammonia-Casale, Lugano (use of hydrogen in industrial plants for producing ammonia and methanol), and several chemical industries are all engaged in hydrogen technology.

Major industries involved in fuel cell technologies are: Sulzer Hexis (presently pilot runs of a natural gas fuelled SOFC for single family houses), HT-Ceramix (development of anode supported SOFC and stack provider) and Elektra Birseck (testing of the PAFC and PMFC fuel cell systems in the 250 kW class). Industries like Hrand Djevahirdjian, Pangas, Linde Cryotech, Ammoniacasale are all concerned with hydrogen technology.

Turkey

- *Foresight Report identifies medium and long-term technological opportunities for the development of transport and stationary applications for PEM, SOFC, and MCFC.*
- *The Boron Institute has been established to investigate the potential of Turkey's abundant boron resources as a hydrogen carrying material in fuel cells.*

Overview

Turkey has engaged in limited work on hydrogen in fuel cells. Most of the effort is driven by the Tubitak Marmara Research Centre (TUBITAK-MRC), involving selected hydrogen related projects and fuel cell development. Turkey has also investigated applications of Boron compounds, which are considered promising candidates among the metal hydrates for the storage of hydrogen. To this end, establishment of the Boron Institute will investigate new application areas for boron and its compounds.

Much of the work on hydrogen is currently oriented toward utilisation in transport and stationary applications on both civil and military levels. In addition, Turkey is also working on:

- Catalytic hydrogen combustion, hydrogen combustion, hydrogen utilisation in PEM fuel cells, hydrogen production from fossil fuels (TUBITAK-MRC).
- Universities in Turkey have been studying on hydrogen energy technologies widely.
- Some private sector entrepreneurs have been studying on application of fuel cells.

A number of policy studies have also been undertaken:

- Energy production plant based on new, renewable and national energy sources.
- Revision to present laws on energy to reach the European Union norms.
- The National Research and Technology Foresight (Vision 2023) has been announced.

Priorities and targets

Turkey has recently announced the National Research and Technology Foresight (Vision 2023), but there is no dedicated national program for hydrogen and fuel cell development. However, the Foresight Report identifies medium and long-term technological opportunities for Turkey, including the development of transport and stationary applications for PEM, SOFC, and MCFC.

International activities

Turkey has participated in a number of EU projects and has also participated in Western European Armament Organisation research areas. This work includes:

- Hydrogen production from diesel for PEM fuel cells (TUBITAK-MRC).

- Hydrogen rich gas production from diesel for MC Fuel cells (TUBITAK-MRC).
- Hydrogen natural gas mixtures (NaturalHy, EU 6th FP project) (TUBITAK-MRC and IGDAS).
- 500 kW Molten Carbonate Fuel-Cell Plant (international project) (TUBITAK-MRC).
- MOCAMI – Small-sized hybrid system with a combination of Molten Carbonate Fuel Cells (MCFC) technology and Micro Gas Turbines.
- IRMATECH – Integrated Research on Materials, Clean and efficient energy Technologies and processes to enhance MCFC in a sustainable development.

Budget

The budget of some selected projects are given below:

- 500 kW Molten Carbonate Fuel-Cell Plant. €4 million for the period 2002-2005.
- Hydrogen production from diesel for PEM fuel cells. €0.5 million for the period 2001-2004.
- Development of PEM Fuel Cell Technologies for the Production of Clean Energy. €2.6 million for the period 2004-2007.
- IRMATECH: €0.12 million.
- MOCAMI: €0.10 million for the period 2003-2006.
- Hydrogen utilisation in vehicles: €0.15 million.
- Hydrogen combustion: €0.35 million.

Key players

- TUBITAK– the Scientific and Research Council of Turkey *http://www.tubitak.gov.tr/english/*
- TUBITAK Marmara Research Centre *http://www.mam.gov.tr/english/escae/index.html*

Other activities

Turkey signed an agreement with the United Nations Industrial Development Organisation (UNIDO) to build in Istanbul a US$40 million International Centre for Hydrogen Energy Technology (ICHET), entirely financed by Turkey. Beyond helping Turkey to increase the amount of energy produced from non-fossil fuels, UNIDO's project is aimed at transferring existing hydrogen technologies from Turkey to other developing countries to help them to catch up with the developed world in the field of renewable energy resources.

Since about 64% of world boron reserves are found in Turkey, scientific studies on boron have been conducted to investigate the potential of boron as a hydrogen carrying material in fuel cells. Turkey is planning to upgrade the utilisation of this natural source, and has invited researchers, investors and international organisations to close cooperate on Hydrogen Energy Studies. Also, the Boron Institute is being established to further this work.

United Kingdom

- ***Fuel Cell Vision Paper sets out short, medium and long term objectives for development and deployment of fuel cells.***
- ***The UK has a world class engineering and industrial base with strong capabilities in system design, packaging and systems integration, and production engineering.***
- ***Focus on improving the attractiveness of the UK as a location for the development and deployment of fuel cells.***

Overview

The UK has a strong fundamental research base that is active in the fields of materials science, catalysis and bio-engineering. At least 22 UK universities have been involved in researching issues associated with hydrogen and a large number of these have ongoing research into chemical and physical hydrogen storage. In addition, UK companies such as BP, Shell and BOC have been active in assessing safety issues related to the storage and distribution of hydrogen.

The UK DTI has been supporting industrial research on fuel cells since 1992 under its Advanced Fuel Cell Programme. The focus of the programme has changed from supporting studies designed to inform the DTI and the industry regarding the prospects for fuel cells to work supporting the development of UK capabilities. Since its inception the program has supported a total of 156 projects involving a total DTI expenditure of £12.4 million. Currently, the program is funded at about £2 million per year.

Over the last year, the UK has aggressively investigated the potential of hydrogen and fuel cells, and has introduced a number of documents to guide the development of its fuel cell industry:

- *Powering Future Vehicles – The Government Strategy* – was published on July 31, 2002. Its objective is that the UK should lead the global shift to clean, low carbon transport. Key elements in the strategy are the adoption of targets for low and ultra low carbon vehicles and the formation of a Low Carbon Vehicles Partnership.
- November 2002: The Technology Roadmap – suggested actions and targets based on published benchmarks for major fuel cell development programs around the world as well as in the UK. A set of development targets were established with the objective of giving the UK a competitive position in certain fuel cell markets.
- February 2003: Review of UK Fuel Cell Commercial Potential – this study provided an assessment of the main applications for fuel cells, the drivers for fuel cells in these areas and the fuel cell technologies likely to be chosen. The UK was assessed both as a potential market for fuel cells and as a supply base, with its strengths and weaknesses used as a basis for identifying key opportunities.
- February 2003: Energy White Paper – the White Paper sets out a strategy for the long term, and to give industry the confidence to invest in a truly sustainable energy future. The paper commits to cutting carbon dioxide emissions by 60% by 2050 and notes the need/potential

of fuel cells to play a greater part in the economy – initially in static form in industry or as a means of storing energy, but increasingly in transport. The paper set the goal that hydrogen will ultimately be generated primarily by non-carbon electricity.

- May 2003: the Fuel Cell Vision, the First Steps – this document is intended to be the starting point for the development of a UK fuel cell vision. It carries forward on the commitments laid out in the Energy White Paper and builds upon the study on the Commercial Potential of Fuel Cells in the UK.
- May 2003: Fuel Cells UK – a new body to drive forward the development of fuel cell technology was launched – Fuel Cells UK is to help the emerging UK sector by helping promote and raise the profile of the fuel cell industry in the UK. It will also act as a central contact point of contact for national and international companies and the research community.
- September 2003: the Fuel Cell Vision Paper – notes that the UK should take a leading role in the development and deployment of fuel cells, and sets out various scenarios for the short, medium and long term. Additionally, it specifies various R&D focus areas and mechanisms for the government to influence the development of the industry.

Priorities and targets

The UK Fuel Cell Vision Paper sets out the following scenarios for the development of the industry:

- Short term: 2003-2007, will focus on demonstrations to prove the economic and technical feasibility of the technology, establish carbon reduction potential, and foster the development of early hydrogen infrastructure. Increasing awareness and benefits will also be included. Building on this Vision, the Government will develop a clear policy framework for fuel cells in order to provide a long-term continuity and a context in which industry can flourish.
- Medium term: 2008-2012, will see value will move downstream, and as a consequence, systems integration and other support will be of increasing prominence. Research will continue to focus on long term challenges in areas such as next generation materials, fuels and fuel processing, integration and manufacturing and automation technologies. Structured and targeted training will help to ensure that skills needs are met.
- Long term: 2013-2023, will see a shift in emphasis towards a much wider spectrum of commercial fuel cell applications, with a diminishing requirement for government intervention. The market will be increasingly consumer driven, and a high proportion of the population will have first-hand experience of fuel cells. Hydrogen infrastructure will continue to grow through the period to support the widespread application of fuel cells (including, towards the end of the period, significant car penetration). Renewables will play an increasingly prominent role. Codes and standards will be revised and updated to reflect new developments. Demonstrations will be driven and funded by industry for incremental improvement.

The UK DTI routemap for fuel cells laid out the following actions: Targets are based on published benchmarks for major fuel cell development programs around the world as well as in the UK.

Activity	Target date
Construct and evaluate a novel SOFC stack with the following characteristics: power density: > 1 kW/litre, capacity: > 50 kWe, CO-tolerant to at least 100 ppm, pressure: < 2 barg, performance degradation < 1% over 1,000 hours	2003
Construct and evaluate a novel SPFC stack of ~ 1 kWe, with a power density of ~ 500 W/litre and operating at ambient pressure	2003
Construct and evaluate a ~ 20 kW SOFC system operating on natural gas	2003
Design, construct and evaluate a compact integrated auxiliary power unit (APU) of ~ 5 kW, together with fuel reforming facilities	2003
Identify in detail those component technologies in which the UK could gain market leadership and the most effective means of supporting the associated development	2003
Ensure that the UK has clear permitting systems/approval frameworks in place for the operation of fuel cell vehicles and power plant. Achieve connection agreements for systems of ~ 1 MW and a few kW	2004
Identify and evaluate a range of possible market enablement measures that are likely to serve UK interests the most effectively	2005
Construct and evaluate a novel, planar SOFC stack of ~ 20 kWe that internally reforms natural gas and delivers an efficiency of > 50% (LHV). The stack should be capable of manufacture using a viable (if not yet proven) process, and with materials costs of less than US$300/kW	2005
Build and evaluate a compact, integrated, self-sustaining system around a ~ 50 kWe SOFC stack, achieving an electrical efficiency of > 40% (LHV)	2005
Design, construct and evaluate a compact, responsive, natural gas fuel processor, scaleable between ~ 1 kW and ~ 50 kW, and hence suitable for residential through to small commercial CHP systems. The system should achieve a power density of > 1 kW/litre, a performance degradation of < 0.5% in 1,000 hours, < 10 ppm CO output, and a 10,000 hour operating life	2005
Design, construct and evaluate a compact, responsive, liquid-fuelled fuel processor, suitable for passenger cars, that achieves a power density of > 1 kW/litre, a performance degradation of < 0.5% in 1,000 hours, < 10 ppm CO output, and an operating life of 10,000 hours	2005
Develop and evaluate a viable hydrogen storage system suitable for passenger cars	2005
Review the prospects for MCFC, DMFC, SOFC	2005
Build and evaluate a pressurized SOFC stack of ~ 50 kWe, complete with immediate BoP and control system	2006

Develop and demonstrate in the UK an integrated pressurized SOFC/gas turbine (GT) hybrid system of ~ 1 MWe, complete with BoP and control system and with well-optimized distribution between SOFC and GT	2008
Evaluate a small fleet of fuel cell vehicles on commercial routes in the UK	2010
Demonstrate a series of at least four fuel cell systems in commercial and residential applications for stationary power in the UK	2010
Subject to the above targets being successfully met: conduct extended field trials of passenger cars throughout the UK; conduct extended field trials of distributed power and CHP fuel cell systems throughout the UK	Post 2010
Subject to the continued good progress of fuel cells towards commercial competitiveness and the provision of energy and environmental benefits, implement a market enablement scheme to encourage widespread market deployment in the UK	Post 2010

Program activities

- DTI New and Renewable Energy Programme. The programme work will: (a) assess technical and commercial prospects for fuel cells; (b) encourage internationally competitive industries in the UK to develop and utilise capabilities for domestic and export markets; (c) quantify potential environmental benefits associated with fuel cells. The work is part of wider programme supporting various technologies with a budget of roughly £18 million per year, from 1992 – onwards.
- Evaluation of 3 hydrogen fuel cell buses in London. €3.75 million for 2001-2006.
- The Tees Valley Hydrogen Project will investigate hydrogen fuelling and hydrogen production from renewable sources.
- EPSRC project is to support basic strategic and applied research and related postgraduate training in the engineering and physical sciences. £1.13 million has been allocated for the period 1998-2003.
- EPSRC Supergen Hydrogen Consortium will explore options for hydrogen as the clean fuel of the future, £3.4 million for the period 2002-2006.

Key players

- The DTI Advanced Fuel Cells Programme. DTI has been supporting industrial research on fuel cells since 1992 under its Advanced Fuel Cell Programme (part of the Renewable Energy Programme).
- EPSRC. The mission of the Engineering and Physical Sciences Research Council (EPSRC) is to support basic strategic and applied research and related postgraduate training in the engineering and physical sciences. The portfolio of projects includes research on photovoltaics, fuel cells,

wind power, wave power, biomass and other technology approaches such as the hydrogen economy.

- The Carbon Trust. The role of the Carbon Trust is to support the innovation required to underpin the commercialisation of new and emerging low carbon technologies.

The UK fuel cells industry

Currently, over 100 UK companies are contributing to the creation of the global fuel cell industry. The knowledge and expertise of the UK industry spans the full commercial value chain, from R&D to systems integration, and from finance to servicing. Many of these capabilities have been developed in partnership with companies and organizations from across the world. The breadth of the UK Fuel Cell Industry's experience encompasses:

- Low temperature fuel cell stacks and components: Here, the focus is on higher value stationary and portable applications. In the longer term, there is the potential to be engaged in high volume markets by exploiting knowledge and experience in scaling production processes.
- High temperature fuel cell stacks and materials: Currently, UK companies are active at the short stack and subsystem level. For the longer term the industry expects to build on this materials research strength to provide competitive advantage through enhanced performance and lower costs.
- Balance of Plant: Significant pockets of skills in component areas such as fuel processors, power conditioning mechanical balance of plant and hydrogen production and storage are important for all fuel cell applications. The UK's engineering capability has a long history of successful innovation creating tangible commercial advantage. The fuel cell industry is demanding such innovation along its supply chain and the UK is in a strong position to deliver.

The UK also has strong capabilities in system design, packaging and systems integration, and production engineering. There are world-class power plant vendors with significant and manufacturing experience in the UK. Important opportunities are therefore likely to exist for UK industry in the design, manufacture, installation and maintenance of fuel cell systems, particularly for stationary power and CHP applications. There are good quality research teams in UK Universities, with world-class expertise in key areas such as materials and catalysis. Equally important is the fact that many of the global energy companies (e.g. Shell, BP) have significant R&D capabilities. Lastly, the launch of The Low Carbon Vehicle Partnership (LowCVP) demonstrates the Government and industry's commitment to promoting the shift towards the use of low carbon vehicles and fuels.

Review of the UK fuel cell vision paper

- Fuel cell and hydrogen businesses already support over 800 jobs in the UK. Forecasts of commercial sales give a global market size of above £20 billion in 2011. There is an opportunity for the UK to build a sizeable industry, centred on fuel cells and the hydrogen economy, covering all stages of the value and supply chain.
- The focus in the near term is to improve the attractiveness of the UK as a location for the development and deployment of fuel cells. Fuel Cells UK already provides a mechanism for UK companies to contribute to this; enhanced mechanisms for dialogue with appropriate parts of Government and global fuel cell companies are needed.

- In the transportation area, the Low Carbon Vehicle (LCV) Partnership has been established to promote the shift to low carbon vehicles and fuels in the UK. Hybrid vehicles feature highly in the Partnership's strategy and the link to fuel cell vehicles is clear. Fuel Cells UK will, as a matter of priority, establish a dialogue with the LCV Partnership and, through this, the UK-based automotive sector (including bus, van and car makers, key component suppliers and designers/developers), the fuel cell sector, and international OEMs to determine initiatives for deploying fuel cell vehicles in the UK.
- The situation in stationary distributed power generation is more complex. The power generation industry is subject to a strong regulatory framework. Demonstrations of fuel cell technology are critical to establishing the case and currently no satisfactory mechanisms exist to support these. Fuel Cells UK will identify key groups to engage with to ensure that appropriate frameworks are in place to encourage the development and deployment of fuel cell distributed power generation in the UK.

United States

- *One of the world leading programs with specific R&D targets and market strategy.*
- *The US National Hydrogen Energy Roadmap (November 2002), set out the national vision for hydrogen.*
- *US Department of Energy (USDOE) is the lead implementing agency.*
- *Major, integrated national programme covering virtually all aspects of HFC R&D and demonstration.*
- *FreedomCAR partnership between USDOE, General Motors, Ford and DaimlerChrysler to develop PEM fuel cells for use in automotive applications.*
- *Strong involvement of industry and individual States's demonstration and deployment initiatives, e.g., California Fuel Cell Partnership.*
- *Power Park concept focuses on the steady production of hydrogen and use of a fuel cell to produce electricity.*
- *FutureGen is a $1 billion, public-private effort to construct the world's first fossil fuel, low-pollution power plant, incorporating new carbon sequestration technologies and producing both electricity and hydrogen.*
- *Program funding over the next five years is $1.7 billion:*
  - *HFC and Infrastructure Initiative is $1.2 billion.*
  - *FreedomCar is $0.5 billion.*

Overview

The United States conducts the vast majority of its R&D on hydrogen and fuel cells under the "Hydrogen, Fuel Cells and Infrastructure Technologies Program," which funds research, development, and validation activities linked to public-private partnerships. The program is led by the US Department of Energy (USDOE) and integrates the activities of a number of US government agencies, including the Department of Defence, the Department of Transportation, and the Environmental Protection Agency. The government's current role is to concentrate funding on high-risk, applied research in the early phases of development to the point where the private sector can make informed decisions on whether or not, and how best to commercialise these technologies. With a fiscal year 2004 budget of US$147 million, the program seeks to implement recommendations in the President's National Energy Policy, the DOE Strategic Plan, the National Hydrogen Energy Vision and Roadmap, and the Hydrogen Posture Plan.

The US National Hydrogen Energy Roadmap (November 2002), describes the principal challenges to be overcome and suggests ways the US can achieve the national vision for hydrogen. The Roadmap stresses the need for parallel development of model building codes and equipment standards to enable technology integration into commercial energy systems, and outreach programs to effectively

educate local government officials and the public, who will determine the long-term acceptance of these technologies. The "Roadmap" drew upon the earlier (February 2002) "National Vision of America's Transition to a Hydrogen Economy – to 2030 and beyond," which outlined a vision for America's energy future powered by clean, abundant hydrogen. This vision document was considered a first step to be used to evaluating hydrogen a long-term solution to America's energy needs.

The US is optimistic about the prospects for hydrogen, not just as the transportation fuel of the future, but also for its potential to generate electricity to heat and power our homes and businesses. Bush stated that he considered his US$1.5 billion hydrogen development plan a legacy for future generations and key to the nation's energy security.

Priorities and targets

In its 2003 report to Congress, USDOE recommended the following program adjustments and public-private cooperative programs to develop and validate technology and to determine if commercialization of fuel cell technology over a wide range of applications is viable by 2015. Throughout the planning process USDOE has envisioned four phases in the transition to a hydrogen economy, each of which requires and builds on the success of its predecessor.

- In Phase 1 government and private organisations will research, develop, and demonstrate "critical path" technologies and safety assurance prior to investing heavily in infrastructure. Public education and codes and standards must be developed concurrently with the RD&D. The President's Hydrogen Fuel Initiative is consistent with completion of the critical path technology RD&D phase leading up to a commercialisation decision in 2015. This Phase could continue beyond 2015 to support basic science and to further develop advanced, sustainable technologies for hydrogen production and use. The commercialisation decision criteria will be based on the ability of hydrogen fuel technology to meet customer requirements and to establish the business case.
- Phase 2 is the Initial Market Penetration Phase. This could begin as early as 2010 using existing natural gas and electric grid infrastructure for applications such as portable power and some stationary and transportation applications, and continue as hydrogen-related technologies meet or exceed customer requirements. As markets are established, this leads to Phase 3, or the Infrastructure Investment Phase, in which there is expansion of markets and infrastructure.
- The start of Phase 3 is dependent on a positive commercialisation decision for fuel cell vehicles in 2015. A positive decision will attract investment in infrastructure for manufacturing fuel cells and for producing and distributing hydrogen. Government policies still may be required to nurture this infrastructure expansion phase.
- Phase 4, which could begin around 2025, is the Fully Developed Market and Infrastructure Phase. In this phase, consumer requirements will be met or exceeded, national benefits in terms of energy security and improved environmental quality will be achieved, and industry will receive adequate return on investment and compete globally. Phase 4 provides the transition to a full hydrogen economy by 2040.

Targets for the general hydrogen and fuel cell R&D, specific targets and objectives for hydrogen production and delivery, specific targets for developing and demonstrating viable hydrogen storage technologies for transportation and stationary applications, and specific targets for the development of fuel cell power system technologies for transportation, stationary, and portable applications are delineated in section 6.2.20, above.

Program activities

The USDOE leads a heavily-funded, wide-ranging HFC programme, working closely with its national laboratories, universities, other federal agencies and industry partners to overcome critical technical barriers to fuel cell commercialization. Current R&D is focused on the development of reliable, low-cost, high-performance fuel cell system components for transportation and buildings applications.

Fuel cell R&D responsibilities at USDOE, include research on SOFC and MCFC with a 2003 budget of US$47 million, of which approximately US$11.5 million is allocated to the Vision 21 projects that develop clean central station generation technologies. The remainder is allocated to technologies that are more focused on distributed generation applications.

The US reports that the development of new materials for improved fuel cell stack and system performance and for lower cost is central to achieving objectives of the DOE effort. Work is ongoing in universities, national laboratories, and industry to identify new materials and fabrication methods for fuel cell membranes, catalysts, and bipolar plates; and to integrate these new materials and methods into fuel cells for testing. Development of enabling technologies has been a success story for the USDOE, where the program is progressing by: (a) developing new membranes for operation at temperatures higher than 120˚C for improved thermal management and impurity tolerance; (b) developing advanced catalyst-coated membranes; (c) developing highly conductive, gas-impermeable bipolar plates and fabrication processes; (d) minimising precious-metal loading; and, (e) assessing and improving component durability.

The US notes that some of the technologies developed for stationary fuel cell applications such as low-cost, compact fuel processors could also be used for off-board processing of fuels to produce hydrogen at vehicle refuelling stations. Thus, the program includes R&D on quick start-up reformers. Ongoing research in industry and national laboratories will focus on improved catalysts and engineering efforts aimed at improving the thermal properties of the fuel processor.

The critical technology development areas are advanced materials, manufacturing techniques, and other advancements that will lower costs, increase durability, and improve reliability and performance for all fuel cell systems and applications. These activities need to address not only core fuel cell stack issues but also balance of plant (BOP) subsystems such as: fuel processors; hydrogen production, delivery, and storage; power electronics; sensors and controls; air handling equipment; and heat exchangers. Research and development areas include:

Polymer Electrolyte Membrane Fuel Cells

- Slightly higher temperature (80-120°C), lower cost membrane materials for more efficient waste heat utilization for cogeneration in stationary/distributed applications or as process heat in a fuel reformer, reducing radiator size for transportation applications and for reduced carbon monoxide (CO) management requirements.
- New, low-cost catalyst materials (reducing or possibly eliminating precious metals) that achieve useful power densities and are resistant to damage from CO or sulphur compounds would benefit both fuel cell and fuel processor technologies.
- A go/no go decision for on-board fuel processing work is scheduled for 2004. The primary criteria for this decision will be the identification of a credible path to achieve a 30-second start-up time target.
- Long life, low cost, and high efficiency air handling equipment to allow operation within weight, volume and cost requirements.

Solid Oxide Fuel Cells

- Stack material and architecture combinations that allow for effective sealing and reduction in life-limiting thermal stresses during thermal cycles.
- Electrolyte/electrode/separator plate material combinations allowing high (over 500 mW/cm^2) power densities at the stack level (not just cells) for achievement of low cost goals.
- Long life, high effectiveness, high temperature heat exchangers for process flow heat recovery subsystems for high system efficiency.
- Stack architectures (including material combinations) that can realistically implement internal reforming leading to reduced costs and long life.

Molten Carbonate Fuel Cells

- Stack materials and configurations to significantly increase power densities above current levels to approach cost targets consistent with large markets.
- Advanced corrosion-resistant materials for stack construction that can result in stack lifetimes in excess of 40,000 hours.

Hydrogen Production, Storage and Infrastructure

- Production technology that enables hydrogen to be produced from domestic sources – initially natural gas and eventually clean coal, nuclear energy, biomass and other renewable sources.
- Compact, lightweight, and cost-effective hydrogen storage systems enabling greater than 300 mile range in all light-duty vehicle platforms.
- Delivery technology capable of providing hydrogen fuel so that when the fuel cell vehicles are commercially available, people can fill them up at their convenience.

Sensors

- Sensor and control technology with the proper ranges and selectivities for integrated fuel cell system application.
- Low cost sensors for detecting hydrogen leaks and other safety related requirements.

Codes and Standards Development

The USDOE addresses codes and standards issues to identify current gaps in the standards development process and to evaluate the adequacy of existing and newly-developed standards. The objectives in this area include facilitating the creation and adoption of model building codes and equipment standards for hydrogen systems in commercial, residential, and transportation applications; and, providing technical resources to harmonize the development of international standards among the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the Global Regulation on Pollution and Energy (GRPE) Program.

The Hydrogen, Fuel Cells & Infrastructure Technologies Program is addressing domestic and international codes and standard issues. The program recognises that affordable hydrogen and fuel cell technologies must be developed and domestic and international codes and standards must be established simultaneously to enable the timely commercialization and safe use of hydrogen technologies. Funding allocations for codes and standards work totalled US$4 million in 2003.

Currently thirteen US and two international SDOs are developing and publishing the majority of the voluntary domestic codes and standards. These organisations typically work with the public and

private sectors to craft standards. In the US, the American National Standards Institute (ANSI) coordinates standards development, provides guidance on consensus building, recommends that no more than one standard is developed per technology, and acts as a central point of contact for the harmonization of international standards.

Safety

The US government is currently drafting a comprehensive safety plan to be completed in collaboration with industry. The plan will initiate the research necessary to fill safety information gaps and allow integration of safety procedures into all USDOE project funding procurements. This will ensure that all projects that involve the production, handling, storage, and use of hydrogen incorporate project safety requirements into the procurements. The USDOE will also publish a handbook of Best Management Practices for Safety by 2010. The US Safety subprogram focuses on the following activities:

- Determining the physical and chemical properties of hydrogen and whether they are accurately reflected in hydrogen's safety classification.
- Conducting safety reviews of current and future projects, including practices and procedures.
- Developing and publishing a comprehensive database on safety, including component reliability, sensors, and hydrogen releases.

Education

The US program is the most comprehensive. The "Hydrogen, Fuel Cells & Infrastructure Technologies Program" includes a subprogram to accomplish the overall objective of educating target audiences about the long-term benefits and near-term realities of hydrogen, fuel cell systems, and related infrastructure. Education activities will rely on internet-based materials to the greatest extent possible, but in addition to building the Program Web site, a library of hard-copy educational materials and a distribution system will also be created in order to provide users and program partners nationwide with access to educational materials. Initial education efforts will focus on teachers and students, state and local governments, and large-scale end-users. Safety and code officials are also top priority audiences, and education activities to serve their needs will be conducted in conjunction with the Safety and Codes and Standards subprograms.

Select HFC Programmes

- Development of high-temperature fuel cell systems, operating on natural gas and syngas (derived from a variety of fuels including coal) for primarily stationary and distributed generation applications. Fuel cell technologies that are supported through this program are SOFC and MCFC. The total funding request for FY 2003 is US$47.0 million, of which approximately US$11.5 million is allocated towards the Vision 21 projects that develop clean central station generation technologies. The remainder is allocated to technologies that are more focused on distributed generation applications. A cornerstone activity is the Solid State Energy Conversion Alliance (SECA), a partnership between DOE, the National Laboratories, and industry to develop and demonstrate planar solid oxide fuel cells for distributed generation applications.
- The US fuel cell activities also focus on the PEM because of its low-temperature operation and capability for fast start up. RD&D program elements include "Cross Cutting PEM Stack and Fuel Processing R&D," which has a budget of US$40 million. USDOE also has a US$7.5 million

program for developing PEMs for stationary applications and a US$7.6 million program for automotive applications. There is also US$10 million budgeted for demonstrating transportation PEM applications in 2004 and US$18 million requested in 2005.

- The FreedomCAR partnership between USDOE and USCAR (a pre-competitive research organization consisting of General Motors, Ford and DaimlerChrysler) is the vehicle through which PEM fuel cells are being developed for use in automotive applications. The goal of FreedomCAR is the development of emission- and petroleum-free cars and light trucks. FreedomCAR focuses on the high-risk research needed to develop the necessary technologies. US$1.2 billion has been pledged by the government for funding the FreedomCAR initiative
- The Hydrogen, Fuel Cells & Infrastructure Technologies Program. The programme recognizes the direct linkage between the need for a robust cost-effective hydrogen infrastructure and the effective utilization of fuel cell technologies. This programme is comprised of three interactive work areas: Hydrogen Production, Hydrogen Storage, and Fuel Cells.
- The US is also developing the "Power Park concept," which focuses on the steady production of hydrogen and use of a fuel cell to produce electricity. When excess hydrogen is available, it is stored for use when electricity demand is high and/or to refuel vehicles. The advantages of producing both hydrogen and electricity in Power Parks include: it provides access to better natural gas rates because of higher volume requirements than for a vehicle refuelling facility only; it facilitates staged implementation of refuelling components to better match the demand from vehicles; and, it allows use of a larger reformer which will lower the per-unit capital costs of hydrogen production. The Power Park concept is amenable to distributed production of hydrogen from natural gas, and opens the possibility of incorporating wind and solar energy effectively. Analysis of the Power Park concept is ongoing and a future test is planned for validation.
- The US is developing "advanced electrolysis' – low temperature electrolysis using alkaline and PEM technologies (electrochemical compression, improved efficiency, lower cost, integration of renewable resources), and "high temperature solid oxide electrolysis' under a US$3.5 million program.
- The French CEA cooperates with the US DOE under the GEN IV umbrella to develop a thermo-chemical (iodine-sulphur process) cycle to produce clean H_2 from heat from nuclear plants. The US also has a US$6.5 million nuclear energy program to convert hydrogen from high temperature heat nuclear sources (and solar) with a projected cost competitive with gasoline.
- The US photolytic program focuses on both photo-biological and photo-electrochemical hydrogen production processes and is funded at US$2.8 million.
- Cross-cutting R&D efforts in the area of metal hydride storage systems.
- Carbon nanotubes and their hydrogen storage capacity are still in the research and development stage, with the focus on improving manufacturing techniques and reducing costs. US DOE work focuses on developing carbon nanotubes as an on-board storage method for hydrogen-fuelled vehicles.
- The US is the only country reporting work on the chemical storage of hydrogen. The US plans a substantial increase in USDOE funding for 2004 to initiate the National Hydrogen Storage Project, which will focus on compressed/liquid H_2 Gas, metal hydrides (including alanates), chemical hydrides, carbon structures, new materials and testing/analysis. US storage R&D objectives are to develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications. US$35.3 million was allocated across various hydrogen storage technology projects in 2003.

- In order to take advantage of abundant coal resources, the US has a US$5 million program aimed at the development of advanced and novel technologies to produce hydrogen from coal, including separation and purification focusing on hydrogen separation membranes, and other technologies including: integrated ceramics, water gas shift membrane reactors, defect free thin films, and inorganic membranes.
- In February 2003 the US announced a new international effort to advance carbon capture and storage technology as a way to reduce greenhouse gas emissions. The project is a US$1 billion, public-private effort to construct the world's first fossil fuel, low-pollution power plant. The plant, known as FutureGen, will serve as a prototype for new carbon sequestration technologies and produce both electricity and hydrogen. The FutureGen initiative will comprise a coal gasification plant with an additional water shift reactor, to produce hydrogen and CO_2. About one million tons of CO_2 (at least 90% of throughput) will then be separated by membrane technology and sequestered geologically. The hydrogen will be burned in a 275 MW generating plant and later in fuel cells. Other common air pollutants such as sulphur dioxide and nitrogen oxides would be cleaned from the coal gases and converted to useable products such as fertilizers and soil enhancers. Mercury pollutants would also be removed.
- The US DOE requested another 10% raise in its 2002 budget for sequestration R&D to over US$20 million annually. The key areas for research include: Absorption (chemical and physical); Adsorption (physical and chemical); Low-temperature distillation; Gas separation membranes; Mineralization and biomineralisation.

Budget

The FY 2003 budget request for the integrated USDOE program is US$97.4 million, split between PEM fuel cell R&D ($57.5 million), and hydrogen production, infrastructure, and storage R&D ($39.9 million). Over the next five years, the Department of Energy will invest $1.7 billion in research and development of hydrogen vehicles and hydrogen infrastructure technologies.

US DOE Funding on Hydrogen Production Fiscal Year 2004:

- $17.3 million: Renewables – direct water splitting using solar energy; thermal processes using biomass; advanced electrolysis from wind power.
- $4 million: Nuclear – using heat from either nuclear power or solar collectors; high temperature water splitting; high temperature chemical cycles.
- $5 million: Coal – separation of pure hydrogen gas from synthesis gas (carbon monoxide and hydrogen); technologies also applicable to biomass feedstocks.
- $12.2 million: Natural gas – small, distributed systems to begin making hydrogen available at local refuelling stations.

Key players

- American Hydrogen Association.
- California Fuel Cell Partnership (CaFCP).
- California Stationary Fuel Cell Collaborative.
- Fuel Cell Test & Evaluation Centre (FCTec).

- FuelCell Energy Inc.
- Fuelcell Propulsion Institute.
- International Partnership for the Hydrogen – IPHE.
- ISE Research Corporation.
- Oak Ridge National Laboratory (ORNL).
- Pacific Northwest National Laboratory (PNNL).
- Partnership for a New Generation of Vehicles (PNGV).
- Science Applications International Corporation (SAIC).
- Umicore Autocat USA, Inc.
- Unitec Ceramics.
- United Defense.
- University of Alabama.
- University of Michigan.
- US Air Force Research Laboratory (AFRL).
- US Army Communications-Electronics Command (CECOM).
- US Army Construction Engineering Research Laboratory (CERL).
- US Army Engineer Research and Development Centre (ERDC).
- US Army National Automotive Centre.
- US Army Research Laboratory (ARL).
- US Army Research Office (ARO).
- US Army Tank–Automobile and Armaments Command (TACOM).
- US Department of Defense (DoD).
- US Department of Energy (USDOE).
- US Fuel Cell Council (USFCC).
- US General Fuel Cell Corporation.
- USCAR.

European Union

Many EU countries have been among the most active worldwide in developing the technologies and concepts for the commercialisation of hydrogen and fuel cells. The EU is seeking to promote greater cooperation, pooling of resources and harmonization of efforts. The goals are the reduction of greenhouse gas emissions in order to meet the EU's Kyoto Protocol commitments, improve the security of energy supply, and promote industrial competitiveness. The long-term EU vision is to have in place an energy supply system based on renewable energies and fuel cells with hydrogen and electricity as prominent energy carriers within 20-30 years.

The European Hydrogen and Fuel Cell Technology Platform

In June 2003, a group of top-level stakeholders in the field of hydrogen and fuel cell technologies – the so called "high level group", presented their report "Hydrogen and fuel cells – a vision of our future". The main objective of this report was to come forward with a vision on the role that both hydrogen and fuel cells could play in achieving sustainable energy, and on how to make that potential into reality in the next twenty to thirty years.

A key recommendation emerged: to set up a European Hydrogen and Fuel Cell Technology Platform, which is aimed at facilitating and accelerating the development and deployment of cost-competitive, world class European hydrogen and fuel cell technologies that will contribute to building a future sustainable energy system. This would differ from current energy system development in two main respects: reduced greenhouse gas emissions and increased security of energy supply.

The European Hydrogen and Fuel Cell Technology Platform, although initiated by the European Commission, is an autonomous body. It has an open structure and is formed by participants that represent a balance of expert knowledge and stakeholder interests. The "beating heart" of the Platform comprises all current EU funded activities in the field of hydrogen and fuel cell technologies (such as projects, initiatives, networks and structures). The aim is to bring other national, regional and local projects and initiatives within the framework of the Platform. In so doing, the currently fragmented RTD effort in Europe would be efficiently harnessed to achieve the vision of the Platform. (see: www.*HFPeurope.org*).

The Alternative Fuels Contact Group

The European Commission set up a stakeholder Contact Group in 2002 to advice technical and economic developments and to promote the use of alternative fuels for road transport, including natural gas and hydrogen. The Contact Group conducted an in-depth study of options for motor fuels for achieving a 20% substitution of diesel and gasoline by these alternative fuels. They provided their views on the potential market penetration of 5% hydrogen vehicles – corresponding to an accumulated 5 million vehicles for 2020, which is the target established by the Commission Communication on alternative fuels (COM (2001) 547). More information: *http://europa.eu.int/comm/energy_transport/envir/2003_report_en.pdf*.

The Hydrogen "Quick Start" Projects

In November 2003, the EC also launched the *European Initiative for Growth* to boost EU economic development. The initiative includes a "Quick Start Programme" with a list of projects for public/private investment in infrastructure, networks and knowledge. The aim is to encourage the creation of public/private partnerships in co-operation with the Member States and the European Investment Bank in order to leverage finance.

The knowledge component of the programme foresees two major ten-year projects for hydrogen-related research, production and use. The first will explore the limits of using hydrogen as a means of de-carbonising today's fossil fuels so as to facilitate their contributions as a bridge to a future hydrogen economy. It aims at advancing cutting-edge research to build a full scale testing and demonstration plant able to produce hydrogen and electricity at an industrial scale and to separate and store safely the CO_2 generated in the process.

The second project will orient and align research and technological development towards exploring the feasibility, from the safety and economic point of view, of managing "hydrogen energy communities", otherwise known as the "hydrogen village", or community within a community. The aim is to study autonomous and grid-connected hydrogen systems exploiting primary renewable energy sources, such as wind, or biomass. At present the budget for these projects is €1.3 billion and €1.5 billion respectively, where public funds should be matched by private investment.

EU Framework Programmes

The main EU funding instruments for research, technological development and demonstration are the Framework Programmes (FP), which are implemented mainly by calls for proposals. The FP5 is well advanced and about to be completed, and the FP6 is currently taking place.

The main objective of FP6 is to contribute to the creation of a true "European Research Area" (ERA). ERA is a vision for the future of research in Europe, an internal market for science and technology. It fosters scientific excellence, competitiveness and innovation through the promotion of better co-operation and coordination between relevant actors at all levels.

The FP6 is structured in different "Thematic Priorities". RTD and demonstration on hydrogen and fuel cells is implemented in thematic priority 6, i.e.: "Sustainable development, global change and ecosystems", which has a total budget of 2,120 M€. Currently €100 million of EU funding, matched by an equivalent amount of public and private investment, is being awarded to research and demonstration projects for hydrogen and fuel cells in the FP6. This will be reinforced via further calls for R&D proposals worth a public and private investment of €300 million (EU funding €150 million).

The following are some of the most important projects on hydrogen and fuel cells that are funded under FP5 and FP6:

Framework Programme 5

- BIO-H2: Hydrogen could be produced using conventional reformer technology fuelled by bio-ethanol – an ethanol/water mixture produced by the fermentation of biomass.

- HYNET: to propose a European hydrogen "roadmap" identifying transition strategies for moving from today's fossil based energy systems to future sustainable energy systems, based largely on electricity and hydrogen.
- EIHPII: global harmonisation of EU regulations for liquid and compressed gaseous hydrogen fuelled vehicles and for the necessary refuelling infrastructure.
- CUTE: Biggest demonstration project worldwide of a fleet of fuel cell powered buses. Complemented by project ECTOS in Iceland.
- FUERO: This cluster of nine projects is setting component and system requirements for fuel cell vehicles.

Framework Programme 6

- MOREPOWER: to develop a low cost fuel cell for portable direct methanol or direct ethanol fuel cells.
- HI2H2: to develop and test an innovative High Temperature Electrolyser for efficient and low-cost production of hydrogen using planar Solid Oxide Electrochemical conversion technologies.
- HYWAYS: in-depth techno-socio-economic analysis of hydrogen production options.
- STORHY: to develop robust, safe and efficient on-board hydrogen storage systems, suitable for use in hydrogen powered Fuel Cell or Internal Combustion Engine vehicles.
- HYSAFE: This Network of Excellence brings together key industrial companies and research organisations on a broad range of hydrogen safety issues for hydrogen vehicles and infrastructures.

Other EU framework projects

The following EU framework programmes have been reported during the survey by various of the participating EU member countries:

- RESH2 – Cluster Pilot Project for the Integration of RES into European Energy Sectors using Hydrogen. The main objective of the project is the integration of RES, hydrogen production and utilization into energy sectors. This is currently being done by designing, constructing and evaluating self-sufficient energy systems driven by wind energy, capable of generating hydrogen, electricity and water making use of the features of hydrogen as an energy vector. The are two demonstration sites: Spain (Canary Islands) and Greece.
- FIRST – FC Innovative Remote system for Telecom. Photovoltaic powering systems are very used in telecom applications when AC Mains is not available due reliability and simplicity reasons. However, solar powering systems have the problem of sun radiation unpredictability, and relatively high cost and size. These problems could be solved using fuel cells in combination of solar powering systems improving power availability and reducing size and cost (this last parameter in medium term following the European Commission predictions). The main objective of this project is to reduce cost and improve availability by taking advantage of the fuel cell performances (very high energy density, zero emission, soundless, simple, modular, portable and potentially low cost in a medium term) for powering remote telecom equipment.
- CEXICELL – Development of Cost Effective and High Quality Planar Solid Oxide Fuel cells by Using Advanced Thermal Spray Techniques. The aims of the project lies in developing Solid Oxide Fuel Cells (SOFC) stacks by using advanced spray techniques never used so far to develop SOFC cells elements. These techniques are: 1) High Velocity Oxi-Fuel Spraying (HVOF); 2) High Frequency Pulse Detonation Spraying (HFPD); 3) Suspension Plasma Spray (SPS); 4) Triplex

Atmospheric Plasma Spray (Triplex APS). These deposition techniques will be used within this project to deposit the various layers in planar SOFC.

- MIGREYD. Modular IGCC concepts for In-Refinery Energy and Hydrogen Supply. Goals: production of hydrogen and enhancing the competitiveness of IGCC (Integrated Gasification Combined Cycle) power plants focusing on applications based on refinery residues. Achievements: Clean and affordable co-production of Hydrogen from residues at IGCC Power Plants. Optimization of the integration of an IGCC in a refinery. Refineries CO_2 emissions reduction. Co-gasification of biomass in IGCC plants. Coupling of gasification with SOFC fuel cells.
- EFFECTIVE: Goals: Holistic integration of MCFC technology towards a most effective systems compound using Biogas as a renewable source of energy.
- SIDMT. Metal Hydrides Manufacturing. Goals: Increase the Hydrogen content in the Metallic Hydrides. Synthesize Metallic Hydrides by conventional techniques and by Self-propagation High Temperature Synthesis.
- FEBUSS Fuel Cell Energy Systems Standardized for Large Transport, BUSses and Stationary Applications. Goals: Fuel Cell Energy Systems Standardized for Large Transport, BUSses and Stationary Applications.
- VIRTUAL FC POWER PLANT. Goals: System-development, Build, Field Installation and European Demonstration of a Virtual Fuel Cell Power Plant, Consisting of Residential Micro-CHPs.
- HSAPS: Technical-economical feasibility analysis of hydrogen introduction in autonomous energy generating systems Goals: The project will first of all establish a broad understanding of the technical and economical market potential for hydrogen SAPS based on local renewable energy sources. This will be a base for industry and governments for promoting new technologies in the existing SAPS market. Secondly, one will identify and quantify the technological and practical issues relevant for the HSAPS market and draw the attention of related industry towards solving problems related to component integration and the needs of the user market. Thirdly, the project will identify the legal, regulatory and administrative hurdles for the HSAPS market development and draw the attention of authorities towards amending such problems. Finally, the project will propose a demo-project plan for H-SAPS installations based on the scientific results obtained during the project.
- CRYOPLANE: "Liquid Hydrogen Fuelled Aircraft-System Analysis". Goals: A large consortium of companies, research institutions and universities of 11 European countries, co-ordinated by Daimler-Chrysler Aerospace Airbus GmbH, in which the Spanish participation was held by CASA and the Polytechnics University of Madrid, run this project. The project objective considered liquid hydrogen as the only known fuel suitable for aviation to be produced from renewable energy sources and offering extremely low pollutant emissions.
- FCTESTNET. Fuel Cells Network for Tests and Standardization.
- Advanced PEM Fuel Cells. APOLLON. Goals: Development and construction of Advance polymeric fuel cells which will be able to operate under H_2 and/or methanol fuels, aiming to thermodynamic efficiencies exceeding 50% with power densities of the order of 1 W/cm^2 and significantly reduced manufacturing cost of the membrane electrodes assembly.
- AMONCO. Advanced Prediction, Monitoring And Controlling of Anaerobic Digestion Processes Behaviour Towards Biogas Usage In Fuel Cells.
- Scale-up of the IP-SOFC to multi-tens of kW Level (MF-SOFC) (Rolls-Royce Fuel Cells systems (UK), Risø National Laboratory (DK), Imperial College of Science, Technology and Medicine (UK), Gaz de France (F), Advanced Ceramics (F)).

- Component reliability in SOFC Systems for Commercial Operation (CORE-SOFC) (Forschungszentrum Jülich (D), Risø National Laboratory (DK), Energieonderzoek Centrum Nederland (NL), Haldor Topsøe (DK), Rolls-Royce (UK)).
- Pressurized IP-SOFC (PIP-SOFC) (University of Genova (I), Rolls-Royce Fuel Cells (UK), Morgan Matroc (UK), Gaz de France, Risø National Laboratory (DK)).
- Integrated Researches on Materials, Technologies and Processes to enhance MCFC (Ansaldo Fuel Cells (I), Frauendhofer Institue for Environment, Safety and Energy Technologies (D), Balcke-Dürr (D), Tubitak – Marmara Research Centre (TR), Centro National de la Recerche Scientifique (F), ENEA (I), Consejo Superior de Investigaciones cientificas (E), Kg. Tekniska Høgskola (S), Centro electrotechnico Sperimentale Italiano (I), EniTechnologie (I), Electric Power Systems (I), Technip/KTI (I), University of Genova (I), Rich Müller (DK)).
- 50 kW PEM fuel cell generator for CHP and UPS applications (50 PEM-HEAP) (IRD Fuel Cells (DK), Gutor Electronic (CH), Energieonderzoek Centrum Nederland (NL), Johnson Matthey Technological Centre (UK), SGL Technologies (D), HGC Hamburg Gas Consult (D)).
- High-temperature PEMFC Stack with Methanol Reforming (AMFC) (Volvo (S), Technical University of Denmark (DK), Statoil (N), NTNU (N), University of Newscastle-Upon-Tyne (UK), Proton Motor Fuel Cell (D)).
- Development of Low-cost, High-efficient PEMFC (APOLLON) (Foundation for Research and Technology Hellas (GR), Max-Planck-Institut für Kohlenforschung (D), De Nora Technologie Elettrochimiche (I), Institute of Chemical Technology (CZ), Consejo superior de Investigaciones Cientificas (E), University of Patras (GR), Technical University of Denmark (DK), Frigoglass (GR), Slovenian National Institute (SL)).
- A 1 kW DMFC Portable Power Generator (PORTAPOWER) (APC Denmark (DK), IRD Fuel cells (DK), Centre National de la Recerche Scientifique (F), Uppsala University (S), Deutsches Zentrum für Luft- und Raumfahrt (D)).
- Thematic network on SOFC Technology (SOFCnet) (Risø National Laboratory (DK) together with 45 European partners from academia and industry).
- Advanced solid polymer fuel cells for operation at temperature up to 200°C (Clc Srl (I), Technical University of Denmark (DK), Foundation for Research and Technology Hellas (GR)).
- Ammonia Cracking (Intema Consult (A), University of Rome (I), Risø National Laboratory (DK), Vito (B), Agrolinz Melemin Gmbh (D), Advanced Lightweight Engineering Bv. (NL), DFG-Energie Institute (D), Graz University of Technology (A), Netherlands energy Foundation (NL)).
- Synthesis, fabrication and characterisation of alternative anodes for direct methane oxidation in SOFC (School of Chemistry University of St. Andrews (UK), University of Aveiro (P), University of Patras (GR), University of Twente (NL), Risø National Laboratory (DK), Forschungszentrum Jülich GmbH (D), BG Plc (UK)).
- Advanced prediction, monitoring and controlling of anaerobic digestion processes behaviour towards biogas usage in fuel cells (Profactor Productionsforschung (A), Consejo Superior de Investigaciones Cientòficas (E), Energieverwertungsagentur – Verein zur Förderung der Sinnvollen Verwertung von Energie (A), University of Agricultural Sciences Vienna (A), Matadero Frigorifico del Nalon (E), Gascon (DK), Slovenska Polnohospodarska Uni v Nitre (SK), EBV Management GMBH & CO.KG (D, Saria Bio-Industries Gmbh (D), Farmatic Biotech Energy AG (D), Biogas Barth GMBH (D), Seaborne Environmental Research (D)).

Useful links and bibliography

The preponderance of information is drawn from the national surveys and reports provided by the participating members of the IEA Hydrogen Co-ordination Group. Information from other sources such as official web sites and national reports have been included.

Web links

Australia

Department of Industry, Trade, and Tourism *www.industry.gov.au(search for "hydrogen")*

Department for Energy and Greenhouse Technologies *www.cegt.com.au*

Perth Fuel Cell Bus Trial *www.dpi.wa.gov.au/fuelcells*

Research Centre for Coal in Sustainable Development *www.ccsd.biz Cooperative*

Ceramic Fuel Cells Limited *www.cfcl.com.au*

Austria

Ministry for Innovation and Technology *http://www.bmvit.gv.at/*

Austrian Energy Agency *http://www.eva.ac.at/*

GE Energy *http://www.jenbacher.com/*

International Institute for Applied Systems Analysis *http://www.iiasa.ac.at/*

Echem Corp. *http://www.echem.at/*

Energie A.G. *http://www.energieag.at/*

Canada

Canadian Transportation Fuel Cell Alliance *http://www.nrcan.gc.ca/es/etb/ctfca/index_e.html*

The Canadian Fuel Cell Industry *http://www.fuelcellscanada.ca/index2.html*

Canadian Hydrogen Association *http://www.h2.ca/*

NRC Institute for Fuel Cell Innovation *http://www.h2fc.com/gov.html*

Hydrogen Early Adopters *http://tpc-ptc.ic.gc.ca./h2/en*

Canadian Fuel Cell Commercialization Roadmap *http://www.strategis.gc.ca/electrical*

National Research Council/Institute for Fuel Cell Innovation *http://ifci-iipac.nrc-cnrc.gc.ca/*

The Natural Sciences and Engineering Research Council /NRC Research Partnership Program *http://www.nserc.ca/*

Natural Resources Canada, CANMET Energy Technology Centre *http://www2.nrcan.gc.ca/es/es/technologies_e.cfm*

Canadian Fuel Cell Industry:A Capabilities Guide *http://www.fuelcellscanada.ca/index2.html*

Denmark

Risø National Laboratory *www.risoe.dk*

Technical University of Denmark, the Interdisciplinary Research Centre for Catalysis *www.icat.dtu.dk*

Haldor Topsøe A/S *www.topsoe.dk*

Technical University of Denmark, Chemical Institute *www.materiale.kemi.dtu.dk*

IRD Fuel Cells A/S *www.ird.dk*

Danfoss A/S *www.danfoss.dk*

University of Southern Denmark *www.sdu.dk/indexE.html*

University of Aalborg, Institute of Energy Technology *www.iet.aau.dk/*

University of Aarhus, Interdisciplinary Nanotechnology Centre *www.inano.dk*

Danish Gas Technology Centre A/S *www.dgc.dk*

Danish Technological Institute *www.danishtechnology.dk*

Folkecenter for Renewable Energy *www.folkecenter.dk/en/*

Finland

Tekes (National Technology Agency of Finland *www.tekes.fi/eng/default.asp*

France

PACo *http://www.reseaupaco.org/*

French Atomic Energy Agency *http://www-drt.cea.fr/*

French Hydrogen Association *http://www.afh2.org/*

ALPHEA *http://www.alphea.com/*

French Scientific Research Center *http://www.cnrs.fr/DEP/prg/Energie.html*

Germany

Bewag *www.innovation-brennstoffzelle.de*

Deutscher Wasserstoff-Verband *www.h2guide.de*

WIBA A.G. *www.wiba.de*

Virtual fairground Hessen *www.brennstoffzelle-hessen.de*

Fuel Cell Network NRW *www.fuelcell-nrw.de*

The German Hydrogen and Fuel Cell Association *http://www.dwv-info.de/e/index.html*

Institute for Materials and Processes in Energy Systems *http://www.fz-juelich.de/portal/oea_iwv_e*

PTJ *http://www.fz-juelich.de/ptj/*

Cooretec *www.cooretec.de*

Greece

Helbio S.A. *http://www.helbio.com*

Italy

Ansaldo Fuel Cells SpA *www.ansaldofuelcells.com*

Arcotronics Italia SpA *www.arcotronics.com*

Centro Ricerche Fiat *www.crf.it*

Ente per le Nuove tecnologie, l'Energia e l'Ambiente *www.enea.it*

Istituto di Tecnologie Avanzate per l'Energia *www.itae.cnr.it*

Istituto per l'Energetica e le Interfasi *www.ieni.cnr.it*

Istituto per la Microelettronica e i Microsistemi *www.imm.cnr.it*

Nuvera Fuel Cells *www.nuvera.com*

Korea

21st Century Frontier Hydrogen R&D Program *http://www.h2.re.kr*

The Korean Hydrogen and New Energy Society *http://www.hydrogen.or.kr*

National RD&D Organization for Hydrogen and Fuel Cell *http://www.h2fc.or.kr*

New Zealand

CRL Energy Limited *http://www.crl.co.nz/*

Industrial Research Limited *http://www.irl.cri.nz/*

Unitec Institute of Technology *http://www.unitec.ac.nz/index.cfm*

The Netherlands

Netherlands Agency for Energy and the Environment *www.Novem.nl*

Energy research Centre of the Netherlands *www.ECN.nl*

Nedstack Fuel Cells and Systems *www.nedstack.com*

Commercial gasses *www.hoekloos.nl*

Dutch Biohydrogen Platform *www.biohydrogen.nl*

Senter *www.senter.nl*

Netherlands Research Council *www.NWO.nl*

Shell Hydrogen *www.shellhydrogen.com*

Spain

Spanish Hydrogen Association *www.aeh2.org*

High Council for Scientific Research Fuel Cells Network *www.csic.es/redes/pilas/pilasc.htm*

Spanish Association for Fuel Cells *www.appice.es*

Spanish Science and Education Ministry *www.csic.es/redes/pilas/pilasc.htm*

Spanish Fuel Cell Association *www.appice.es*

Propulsion and Energy Division of IZAR *http://www.izar.es/cgi-bin/pye.dll/propulsion/jsp/home.do*

DAVID Fuel Cell Components *www.davidfcc.com*

NTDA Energia *www.ntdaenergia.com*

Ajusa S.A. *www.ajusa.es/pilas_combustible/pilas_combustible.htm*

Sweden

Lund University Photosynthesis Group *http://www.biokem.lu.se/AFS-WWW/index.htm*

Elforsk *http://www.elforsk.se/varme/varm-bcell.html*

Jungner Center *http://fuelcell.mvs.chalmers.se/*

Sydkraft (E.ON Group) *www.sydkraft.se*

The Swedish National Energy Agency *http://www.stem.se/english*

Switzerland

Enet Swiss Energy *www.energy-research.ch*

Paul Scherrer Institute *www.psi.ch*

Sulzer Hexis *www.hexis.ch*

Turkey

TUBITAK – the Scientific and Research Council of Turkey *http://www.tubitak.gov.tr/english/*

TUBITAK Marmara Research Centre *http://www.mam.gov.tr/english/escae/index.html*

UK

UK Department of Trade and Industry
http://www.dti.gov.uk/energy/renewables/technologies/fuel_cells.shtml

DTI *http://www.dti.gov.uk/energy/publications/pdfs/carbrevfuelcell.pdf*

DTI *http://www.dti.gov.uk/energy/publications/pdfs/index.shtml*

DTI White Papers *http://www.dti.gov.uk/energy/publications/whitepapers/index.shtml*

Fuel Cells UK *http://www.fuelcellsuk.org/*

Ninth Grove Fuel Cell Symposium *http://www.grovefuelcell.com/*

Powering Future Vehicles: The UK Government Strategy
http://www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_024731.pdf

The Carbon Trust *http://www.thecarbontrust.co.uk/TheCarbonTrust/Default.htm*

The Engineering and Physical Sciences Research Council (EPSRC)
http://www.epsrc.ac.uk/website/index.aspx

UK Sustainable Hydrogen Energy Consortium (SHEC) *http://www.shec.bham.ac.uk/*

UK Hydrogen Energy Network (H_2NET) *http://www.h2net.org.uk/*

US

American Hydrogen Association *http://www.clean-air.org/*

California Fuel Cell Partnership (CaFCP) *http://www.fuelcellpartnership.org/*

California Stationary Fuel Cell Collaborative *http://stationaryfuelcells.org/*

Fuel Cell Test & Evaluation Centre (FCTec) *http://www.dodfuelcell.com/test_eval/*

FuelCell Energy Inc *www.fce.com*

Fuelcell Propulsion Institute *http://www.fuelcellpropulsion.org/*

International Partnership for the Hydrogen – IPHE *http://www.iphe.net/*

ISE Research Corporation *http://www.isecorp.com/*

Oak Ridge National Laboratory (ORNL) *http://www.ornl.gov/*

Pacific Northwest National Laboratory (PNNL) *http://www.pnl.gov/*

Partnership for a New Generation of Vehicles (PNGV) *http://www.fueleconomy.gov/feg/pngv.shtml*

Science Applications International Corporation (SAIC) *http://www.saic.com/*

Umicore Autocat USA, Inc. *http://www.umicore.com/*

Unitec Ceramics *http://www.ucm-group.com/UCL/frames.htm*

United Defense *http://www.uniteddefense.com/*

US Air Force Research Laboratory (AFRL) *http://www.afrl.af.mil/*

US Department of Energy (USDOE) *http://www.energy.gov/engine/content.do*

US Fuel Cell Council (USFCC) *http://www.usfcc.com/*

USCAR *http://www.uscar.org/*

Other sources

- *http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html*
- HYDROGEN AND FUEL CELL ACTIVITIES IN WESTERN EUROPE, T. Alleau, WHEC 2002, Montreal, Canada *http://www.h2euro.org/publications/docs2002/EHA_WHEC14_JUNE2002.pdf.*
- *http://www.electricauto.com/Fuel-Cell_Program.html*
- *http://www.fct.ca/30_10_03.html*
- CTFCA Website *http://www.nrcan.gc.ca/es/etb/ctfca/index_e.html*
- h2 early adopters programme website *http://tpc-ptc.ic.gc.ca/h2/en/about.html*
- From files: CDXHIA_EXCO_OCTOBER_2003/Canada_Rep_Beck
- BACKGROUNDER: VANCOUVER FUEL CELL VEHICLE PROJECT *http://www.h2fc.com/gov.html*
- Beck powerpoint.
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